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Fertilizer and Paclobutrazol Effects on Petunia Production and Post-production Performance

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FERTILIZER AND PACLOBUTRAZOL EFFECTS ON PETUNIA PRODUCTION AND POST-PRODUCTION PERFORMANCE

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ABSTRACT

Reducing the amount of fertilizer applied to the plants in ornamental plant production industry is a growing trend due to rising environmental concerns; however, reduced fertilization can result in the failure to supply the retail customer with a plant that contains enough nutrients to sustain further growth in the consumer environment where fertilizer application is frequently lacking. Therefore, the objective of the first study was to examine alternative fertilizer delivery strategies that can maintain petunia quality during greenhouse production and continue to sustain plant growth and flowering in the post-production consumer environment. The fertilizer treatments applied to the plants were defined by a 4×3×3 factorial consisting of four constant liquid fertilization (CLF) concentrations (0, 50, 100, or 200 $mg \cdot L^{-1}$ N), three controlled-release fertilization (CRF) concentrations (0, 2.4, or 4.7 $kg \cdot m^{-1}$), and three pulse fertilization (PF) concentrations (0, 300, or 600 $mg \cdot L^{-1}$ N). The results showed that both CRF and PF had positive effect on growth and flowering of the finished product quality as well as during the subsequent post-production consumer performance. The only negative effect observed in the increased fertilization treatment was the additional growth that occurred during the greenhouse phase. So, a second study was designed to examine the interaction between CLF and plant growth regulator, paclobutrazol (*rac*-(2*R*,3*R*)-1-(4-chlorophenyl)-4,4-dimethyl-2-(1*H*-1,2,4-triazol-1-yl)pentan-3-ol). Paclobutrazol application is a common practice in bedding plant production in order to achieve a more compact plant that increases shipping capacity and tolerance to postharvest handling stresses. The fertilizer and paclobutrazol treatments applied to the plants were defined by a factorial combination of four CLF concentrations

(50, 100, 150, or 200 $mg \cdot L^{-1}$ N) and four paclobutrazol concentrations (0, 5, 10, or 20 $mg \cdot L^{-1}$). The results showed that paclobutrazol successfully reduced the growth of plants in the high CLF treatments, but also continued to reduce plant growth and flowering throughout the post-production phase. From these observations we conclude that when applied at the proper rate, paclobutrazol can improve the finished product quality as well as post-production performance, but excessive paclobutrazol application results in poor growth in the consumer environment.

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CHAPTER ONE

INTRODUCTION

The high value of greenhouse crops demands intensive production methods such as frequent fertilization and irrigation (Roude et al., 1991). Thus, commercial greenhouse growers in the United States have historically applied relatively high concentrations of nutrients to maximize crop performance and reduce production time (Cabrera, 2003; Cardarelli et al., 2010; Klock-Moore and Broschat, 2001). Moreover, container-grown plants require frequent irrigation because of the small volume of growth medium held within the container (Warsaw et al., 2009; Wang et al., 2012). Petunias (*Petunia ×hybrida* Hort. Vilm.-Andr.) are considered to be relatively 'heavy feeders' (Dole et al., 2002; Zhang et al., 2012), and therefore nutrient management through fertilization is a key factor in the production of high-quality plants.

Among plant mineral nutrients, nitrogen (N) has the largest effect on plant growth and crop productivity, and thus N optimization is very important in fertigation (Cabrera and Devereaux, 1998; Martín et al., 2007). Nitrogen is the main plant nutrient needed for chlorophyll production and other plant cell components such as proteins, nucleic acids, and amino acids (Muñoz-Huerta et al., 2013). It is part of various enzymatic proteins that catalyze and regulate plant growth processes (Sinfield et al., 2010). Therefore, crop yield and biomass are highly affected by N fertilization (Tremblay et al., 2011). However, excessive fertilization results in fertilizer runoff and has become an increasingly important environmental concern due to potential nitrate (NO_3^-) contamination of groundwater (Klock-Moore and Broschat, 1999; Klock-Moore and Broschat, 2001; Martín et al., 2007).

Water leached from containers carries nutrients and potentially other contaminants such as pesticides and may promote movement of contaminants into surrounding water supplies (Warsaw et al., 2009). Moreover, the amount of N applied to greenhouse crops is typically greater than those for field crops on an area basis (Martín et al., 2007). The United States Environmental Protection Agency estimates that nitrates are present (0.15 $mg \cdot L^{-1}$) in over one-half of the wells in the U.S. that are used for drinking water (National Pesticide Survey, 1990). Therefore, regulations to control environmental pollution by greenhouse industry are increasing (Molitor, 1990) and consequently, greenhouse growers are reducing the amount of fertilizer applied to their crops. As excessive nutrients do not necessarily translate into higher profits for ornamental production (Cardarelli et al., 2010), this changing trend in greenhouse production might seem applicable. However, since most consumers do not fertilize their plants after the purchase, lower fertilization rates during production may result in reduced consumer performance due to lack of nutrients within the container at the point of sale.

In this thesis, the effect of different fertilizer delivery strategies was assessed that can improve consumer performance without damaging product quality. The following topics are addressed in the review of the scientific literature: role of nutrition on plant growth, foliar greenness, and post-production performance, and the potential usage of controlled release fertilizer (CRF) as an alternative form of delivering fertilizer to the ornamental plants.

CHAPTER TWO

LITERATURE REVIEW

Plant Nutrition and Plant Growth

Biomass. Higher fertilizer concentrations often produce larger plants (Alem et al., 2014). In petunia, it was reported that shoot dry mass more than doubled as fertilizer concentration increased from 100 to 200 $mg \cdot L^{-1}$ N. When petunia (*Petunia ×hybrida* Hort. Vilm.-Andr.) and impatiens (*Impatiens walleriana* Hook.f.) were grown with CRF (Osmocote 14N–6.2P–11.6K), shoot dry mass increased linearly as fertilizer rate increased from 1.25 to 7.5 $kg \cdot m^{-3}$ (Klock-Moore and Broschat, 1999). However, higher than optimal nutrient concentrations can depress plant growth. Frett et al. (1985) compared growth of petunias fertilized with 0, 100, 200, or 400 $mg \cdot L^{-1}$ N and the highest growth (dry weight, branch length, and flowering) was observed with 200 $mg \cdot L^{-1}$ N. In pansies (*Viola ×wittrockiana* Gams.) grown with an electrical conductivity (EC) of 0.15, 1.0, 2.0, or 3.0 $dS \cdot m^{-1}$ (N at 0, 135, 290, or 440 $mg \cdot L^{-1}$), the 2.0 $dS \cdot m^{-1}$ treatment resulted in the greatest plant growth (van Iersel and Kang, 2002). In ornamental pepper (*Capsicum annuum* L.), shoot dry mass, leaf area, and plant height was highest at 200 $mg \cdot L^{-1}$ N among 100, 200, 300, or 400 $mg \cdot L^{-1}$ N treatments (Kang et al., 2004). In woody ornamental plants, tissue N concentrations increased in a typical saturation response with N supply (Cabrera, 2003; Cabrera and Devereaux, 1998). When containerized crape myrtle (*Lagerstroemia indica ×fauriei*) plants were grown with 15 to 300 $mg \cdot L^{-1}$ N, higher concentrations than 60 $mg \cdot L^{-1}$ N depressed plant growth.

Zhang et al. (2012) reported that there was a significant positive correlation (R = 0.735, $P < 0.01$) between the accumulation of N, phosphorus (P), and potassium (K) and dry matter in petunias, suggesting that the nutrient demands of petunias may be estimated indirectly by dry matter accumulation. This might be useful for estimating required fertilization level for different cultivars of petunia. In this study, N was reported to be in the highest demand for petunia growth and flowering, with mean NPK uptake ratios of 1:0.11:0.71.

Root to Shoot ratio. Nitrogen also affects the root to shoot ratio. Root to shoot ratio of petunia and begonia (*Begonia semperflorens-cultorum* Hort.) decreased as fertilizer EC increased from 0.12 to 2.77 $dS \cdot m^{-1}$ (Nemali and van Iersel, 2004). When pansies were grown with fertilizer EC of 0.15, 1.0, 2.0, or 3.0 $dS \cdot m^{-1}$ (0, 135, 290, or 440 $mg \cdot L^{-1}$ N, respectively), they showed an increase in root dry mass and a large decrease in root to shoot ratio as fertilizer EC increased from 2.0 to 2.5 (van Iersel and Kang, 2002). In crape myrtle, increase in N significantly favored shoot over root growth (Cabrera and Devereaux, 1998). In peace lily (*Spathiphyllum*), root to shoot ratio increased under N, P, and iron (Fe) deficiencies, but decreased under calcium (Ca) and boron deficiencies (Yeh et al., 2000).

Such response might be a result of plants' inherent tendency towards maintaining homeostasis, particularly in terms of carbon, nitrogen, and water (Cabrera and Devereaux, 1998). In this case, a plant allocates more resources to the most limiting factor until all factors become equally limiting. This explains the decrease in root to shoot ratio under increasing N supplies. Assuming that there is an adequate water supply, carbon becomes the limiting factor and the plant allocates more resources to shoot growth, in particular leaf

area, rather than root growth. On the other hand, a nutrient limitation induces and increases root to shoot ratio (Ingestad and Ågren, 1991). This response is explained by a plant's mechanism to adjust to an imbalance of exogenous resources by allocating new biomass to the organs that are involved in acquiring the scarcest resources (Hermans et al., 2006). In other words, a low nutrient supply from the root medium is compensated by increased root growth.

Nitrogen Form. Greenhouse growers commonly use the form of N to control shoot size (Nelson et al., 2012). There are two N forms available for plant use: nitrate (NO_3^-) and ammonium (NH_4^+). It is believed that fertilizers with high proportions of NO_3^- produce compact shoots (smaller leaves and shorter internodes), whereas those with high proportions of NH_4^+ yield large shoots. The reasoning behind this response is the adverse effect of high NO_3^- supplies on uptake and utilization of anion such as sulfate (SO_4^{2-}), and thus plant growth (Cabrera and Deveraux, 1998). Nelson et al. (2012) reported a strong inverse relationship between the phosphate supply and compactness of gomphrena (*Gomphrena globosa* L.), impatiens, petunia, marigold (*Tagetes erecta* L.), and tomato (*Solanum esculentum* Mill.). However, the relationship between proportion of NO_3^- and compactness was comparatively small, indicating that the limited phosphate level in high NO_3^- fertilizers account for compactness rather than the high proportion of NO_3^-.

Phosphorus (P) is reported as an essential plant nutrient for optimal plant quality following N, since process of energy exchanging is impossible without it (Fernández-Falcón et al., 2006). In petunia and begonia, P deficiency was reported to induce increased dry mass, height, width, and flower number (James and van Iersel, 2001). Very often

delaying of flowering is also observed in P deficient plants (James and van Iersel, 2001; Justice and Faust, 2015; Nowak and Stroka, 2001). In P-deficient New Guinea impatiens, reduced plant height, width, shoot number, and leaf number was observed (Nowak and Stroka, 2001). It was reported that high N and high P create a synergistic effect, increasing plant growth more than either alone. The P status in plants has a direct effect on nitrate reductase concentrations, which are high at high P levels and low at low P levels. Justice and Faust (2015) demonstrated that the delayed flowering is due to the slower rate of node development rather than a delay in flower initiation, since there was no significant difference observed for the number of nodes below the first open flower across all treatments.

Plant Nutrition and Foliar Greenness

In ornamental plants, the degree of foliar greenness is one of the most important parameters in determining their marketability (Wang et al., 2005). The degree of leaf greenness is directly related to chlorophyll concentration and therefore, leaves with high chlorophyll contents not only show increasing greenness visually but also indicate sound growth of plants physiologically. Plant leaf chlorophyll contents are closely related to plant's leaf N status. It was reported in various horticultural and agronomic crops that N fertilization increased foliar N content and leaf chlorophyll levels (Cabrera, 2003; Cabrera and Devereaux, 1998; Demotes-Mainard et al., 2008; Kang et al., 2004; Najm et al., 2012; Wang et al., 2012; Yeh et al., 2000).

Nitrogen is considered the most basic plant nutrient, since it is the nutrient that most limits photosynthesis (Fernández-Falcón et al., 2006). Photosynthetic proteins account for

more than half of the N in a leaf (Evans, 1989). Nitrogen is a part of enzymes participating in the chlorophyll synthesis and is a fraction of chlorophyll molecule (Najm et al., 2012). Thus, increasing N fertilizer application can result in an increase in the plant N uptake and leaf chlorophyll concentration. However, in some cases, ammonium toxicity may interfere with this positive correlation between leaf chlorophyll and N content. If plants uptake excessive ammonium ions, toxicity may develop and this affects chloroplast structure (Puritch and Barker, 1967) and therefore chlorophyll production. For petunia plants, Fe can also significantly affect foliar greenness since they are categorized as an Fe-inefficient plants (Šrámek and Dubský, 2009). Petunias are very susceptible to neutral and above pH, and react by decreasing Fe uptake followed by chlorosis and growth depression. High substrate pH can also limit the uptake of manganese (Mn), and it has similar deficiency symptoms as Fe.

Plant Nutrition and Post-production Performance

Post-production or consumer performance of flowering potted plants has become a primary area of concern for commercial producers, floral buyers, and consumers (Nell and Hoyer, 1995). It has been estimated that post-production losses can account for up to 20% of floricultural products becoming damaged and/or sold at reduced prices (Andiru et al., 2013). Healy (2009) reported that only 12% of the seeds or cuttings started by the propagation industry ultimately survive in a garden. Genetic sources and production environments have been shown to mainly influence the post-production performance of flowering potted plants (Nell and Hoyer, 1995). Identification of the source of origin in product marketing and quality testing in nurseries indicate that cultural conditions have an

equally strong influence on the post-production quality of potted plants as have their genetic characteristics (Hendriks, 2001). Nell et al. (1997) reported that mineral nutrition was the most important production factor affecting the post-production longevity and quality of potted flowering plants. The key factors affecting consumer satisfaction of flowering potted plants were reported to be flower quality (color and flower number) and longevity (Ferrante et al., 2015; Macz et al., 2001). Other important characteristics are also primarily defined by visual appearance, such as plant's shape, which should be compact and well- branched (Morrel et al., 2012). Fast growth and development are also preferred so that the plants can reach the commercial stage as soon as possible (Ferrante et al., 2015). Nell et al. (1989) and Roude et al. (1991) proposed that these factors can be achieved by proper production management, especially N fertilization. The most common post production disorder is represented by leaf yellowing, which is mainly due to chlorophyll degradation combined with absence of new biosynthesis (Ferrante et al., 2015). A likely correlation between the N supply during cultivation and the post-production quality of the plants under interior conditions was observed in chrysanthemum (*Dendranthema grandiflora*) (Nell et al., 1989), *Campanula carpatica* (Serek, 1990), and *Schefflera* (Braswell et al., 1982).

No absolute standards exist for post-production performance due to the wide diversity of floriculture crops (Nell and Hoyer, 1995). In some plants, increasing fertilizer level increases post-production quality. When fertilizer application was terminated on petunias once visible flower bud stage occurred, there was a decline in dry mass, flower number, visual rating, and post-production longevity (Armitage, 1986). Lowering

fertilization to 50% of the recommended level in chrysanthemum shortened production longevity and lengthened production time (Chau and Heinz, 2006). In red-currant coprosma (*Coprosma rhamnoides*), post-production leaf abscission was reduced when the plants were fertilized with 400 $mg \cdot L^{-1}$ N compared to 200 $mg \cdot L^{-1}$ N (Hong and Suh, 2012). One or no leaves abscised when plants received 2 or 4 g/pot CRF (Osmocote 14N–6P–8.2K), regardless of constant liquid fertilization (CLF) concentration. This response was correlated with high tissue N concentration. On the other hand, increasing the supply of nutrients has an adverse effect on the post-production performance of some plants. Kalanchoe (*Kalanchoe blossfeldiana*) lasted 4 days longer in post-production environment when fertilized with 150 $mg \cdot L^{-1}$ N compared to 600 $mg \cdot L^{-1}$ N (Leonard and Nell, 2000). In chrysanthemum, application of 50 $mg \cdot L^{-1}$ N resulted in maximal post-production inflorescence longevity, although it did not produce saleable plants (Macz et al., 2001). Postharvest longevity was significantly reduced with 150 or 200 $mg \cdot L^{-1}$ N. Another study (ter Hell and Hendriks, 1995) showed a correlation between rising N amounts in substrates and low post-production quality of New Guinea impatiens, pot roses (*Rosa hybrida*), and poinsettias (*Euphorbia pulcherrima*). The percentage of bud drop (or leaf drop for poinsettias) increased as fertilizer concentration increased from 50 to 150 $mg \cdot L^{-1}$ N for impatiens, from 100 to 200 $mg \cdot L^{-1}$ N for roses, and from 100 to 300 $mg \cdot L^{-1}$ N for poinsettias. With increasing supply of N, especially NH_4^+, premature leaf/bud drop under post-production conditions was observed. An excessive N fertilization leads to the higher substrate salt content. This in turn increases root damages, indirectly lowering the post-production quality of plants. Regardless of the amount of N applied, lack of sulfur (S)

fertilization was found to lower post-production quality, showing yellowish foliage, stunted growth, minimal leaf area, delayed bud set, and first flower color, and delayed or no inflorescence anthesis in chrysanthemum (Macz et al., 2001).

Controlled Release Fertilizer

Controlled Release Fertilizer (CRF) refers to a granulated fertilizer designed to gradually deliver nutrients to plants at rates and amounts that match the nutrient requirement of the plants (Medina et al., 2008; Tian and Saigusa, 2002). Compared with conventional water-soluble N fertilizers (constant liquid fertilizer, CLF), CRFs have an advantage of controlling the rate of N fertilizer dissolution, thereby increasing the utilization efficiency of N fertilizer by plants (Tian and Saigusa, 2002). Because of the relatively higher costs of CRFs compared with CLFs, currently CRFs are only a very small portion of the fertilizer market and are primarily used in special crops, e.g., professionally maintained turf such as golf courses and parks, home grounds, and in the floriculture and nursery fields (Lunt, 1971; Medina et al., 2008; Tian and Saigusa, 2002). A wide variety of CRF materials is available, varying in release duration from 3 to 24 months (Sharma, 1979).

The basic approaches used to create CRFs are: [1] cover water-soluble fertilizer salts with a physical barrier; [2] use materials of limited water solubility containing plant-available N forms (e.g., metal ammonium phosphates); [3] use materials of limited water solubility that release plant-available N (e.g., the urea forms, oxamide) during chemical and/or microbial decomposition; [4] use water-soluble or relatively water-soluble N sources that gradually decompose, releasing plant-available N (e.g., guanylurea salts) (Tian

and Saigusa, 2002). Coated fertilizers are the most popular form of CRF for containerized nursery crop production in North America (Hicklenton and Cairns, 1992; Sharma, 1979; Tian and Saigusa, 2002). Various materials can be used as coatings for solid N fertilizer, and the most commercially important are waxes, sulfur, and polymers.

As mentioned above, the CRF nutrient release pattern is usually synchronized with the growth rate of crops, and thus the N recovery of CRFs by crops is much higher than that of water-soluble fertilizers (Tian and Saigusa, 2002). Increasing the recovery of N fertilizers means less N entering into the environment. The use CRF has also been identified as a best-management practice because CRFs supply localized nutrients to the surrounding substrate over a period of time, limiting the nutrient loss via leaching and run-off (Andiru et al., 2013; Haver and Schuch, 1996; Klock-Moore and Broschat, 1999; Sharma, 1979; Tian and Saigusa, 2002). Simple application method and reduction in the frequency of application also can reduce production costs (Lunt, 1971; Sharma, 1979; Tian and Saigusa, 2002). Another important positive aspect of CRFs is the improvement of post-production value by making nutrients available even after the production phase (Chiari et al., 1999) and promoting a better acclimatization of the plant in the retail display or home environment (Sharma, 1979). When plants are moved from a greenhouse production environment to a retail outlet or to an outside landscape, they often experience abiotic stress due to sub-optimal post-production environmental conditions (Andiru et al., 2013). Nell et al. (1997) showed that plants that received continuous fertilization in the landscape produced more flowers, which is a preferred characteristic due to the added aesthetic quality of the plant. Retailers can promote the beneficial effects of a CRF as a value-added

product that requires less plant care in the landscape, while reducing mineral nutrient losses into the environment during production (Andiru et al., 2013).

Paclobutrazol

Most annual ornamental plants produced in high density situations tend to grow taller than desired and thus benefit from the use of plant growth regulator (PGR) to control height (Baloch et al., 2013; Ilias and Rajapakse, 2005). From a production standpoint, a high-quality plant is one that is not stretched, well branched, and narrow enough to minimize entanglement with its neighbors and allow for dense packing on delivery trucks (Carey et al., 2008).

Paclobutrazol (*rac*-(2*R*,3*R*)-1-(4-chlorophenyl)-4,4-dimethyl-2-(1*H*-1,2,4-triazol-1-yl)pentan-3-ol) is a widely used PGR in the bedding plant production (Keever and Kessler, 2008). It inhibits gibberellin synthesis within the plant that is responsible for cellular elongation (Baloch et al., 2013; Buchenauer, 1977; Hedden and Graebe, 1985). Besides reducing height, PGRs can promote uniform flowering, darken leaf color, decrease new leaf expansion, and extend the life of certain species (Baloch et al., 2013; Fishel, 2015). Other benefits include proportional plant size with the pot, increased shipping capacity, and increased tolerance to handling stresses which improves plant shelf life and marketability (Latimer and Whipker, 2012). Plant growth regulators are most effective when applied at the appropriate times, which is just prior to active shoot growth. This is typically one or two weeks after transplanting a plug. Late application should be avoided, especially in the case of triazoles such as paclobutrazol, because they may delay flower opening when applied after flower initiation.

Although paclobutrazol is highly effective on most crops, it metabolizes slowly and therefore, its effects can extend well beyond application during production to affect post-production plant performance (Baloch et al., 2013; Ilias and Rajapakse, 2005; Keever and Kessler, 2008). The half-life period of paclobutrazol in a plant or soil is in the range of several months, whereas compounds such as prohexadione-Ca are much more rapidly degraded (Rademacher, 2000). The residual effect of paclobutrazol may delay flowering and inhibit branching (Carey et al., 2008; Ilias and Rajapakse, 2005). Growers often have problems with paclobutrazol causing excessive height reduction and slow growth after transplanting. In sensitive plants, excessive stunting can be persistent (Latimer and Whipker, 2012). In perennial verbena (*Verbena canadensis* L.), high concentration of paclobutrazol reduced the number of marketable plants due to nonsymmetrical appearance on some of the plants (Arnold, 1998). Paclobutrazol was not distributed uniformly, resulting in the failure of some branches to reduce their internodal growth.

Plant growth regulators can be applied either as a foliar spray or a substrate drench. Most PGRs are applied as a spray, after which they are absorbed via the leaves and translocated to the growing shoot tissues (Rademacher, 2000). However, compounds such as paclobutrazol or uniconazole are translocated almost entirely acropetally and are not absorbed as effectively by shoot parts as others. Thus, paclobutrazol is often applied as a soil drench. The benefits of drench application include more uniform and longer-lasting effect and a less negative effect on flowering or flower size (Latimer and Whipker, 2012). Despite these advantages, drenches are less commonly used on perennials due to their higher application costs of handling individual pots. Nonetheless, the substrate drench

method has shown greater control of plant growth on chrysanthemum, Easter lily (*Lilium longiflorum*), and poinsettia (Tayama et al., 1992). In osteospermum (*Osteospermum ecklonis*), foliar sprays of ≤80 mg·L^{-1} paclobutrazol were ineffective in controlling plant growth (Gibson and Whipker, 2003). However, substrate drenches of paclobutrazol at 16 mg/pot limited plant height by 21% compared to the untreated control and flowering was not affected. When potted black iris (*Iris nigricans* Dinsm.) plants were sprayed with 100, 250, 500, or 1000 mg·L^{-1} paclobutrazol, they resulted in curved leaves (Al-Khassawneh et al., 2006). When they were drenched with 0.25 or 1 mg·L^{-1} paclobutrazol, there was a significant reduction in plant height as well as an increase in flowering by 12% compared to untreated plants. However, substrate drenches of paclobutrazol at 2 mg·L^{-1} reduced flowering to 80% and excessively reduced plant height and leaf weight.

CHAPTER THREE

FERTILIZATION STRATEGIES DURING GREENHOUSE PRODUCTION AFFECT PETUNIA GROWTH AND FLOWERING IN THE GREENHOUSE AND THE POST-PRODUCTION ENVIRONMENT

Introduction

The high value of greenhouse ornamental crops and the relative short production schedules demand intensive production methods such as frequent fertilization and irrigation (Roude et al., 1991). Thus, commercial greenhouse growers in the United States have historically applied relatively high concentrations of nutrients to petunias, e.g., 250-350 $mg \cdot L^{-1}$ N, to maximize crop performance and reduce production time (Dole et al., 2002). Additionally, fertilizer is relatively inexpensive, so growers have had a tendency to err on applying excess fertilizer to avoid non-optimal growth and nutritional deficiencies. Petunias (*Petunia ×hybrida* Hort. Vilm.-Andr.) are considered to be relatively 'heavy feeders' (Zhang et al., 2012), and therefore nutrient management through fertilization is a key factor in the production of high-quality plants.

Excessive fertilizer application results in nutrient runoff and has become an increasingly important environmental concern due to potential nitrate and phosphate contamination of groundwater (Klock-Moore and Broschat, 1999). Water leached from containers carries nutrients and potentially other contaminants such as pesticides and may promote movement of contaminants into surrounding water supplies (Warsaw et al., 2009). Moreover, the amount of N applied to greenhouse crops is typically greater than those for field crops on an area basis (Martín et al., 2007). The United States Environmental Protection Agency estimates that nitrates are present (0.15 $mg \cdot L^{-1}$) in over one-half of the

wells in the U.S. that are used for drinking water (National Pesticide Survey, 1990). Therefore, regulations to control environmental pollution are a concern of the greenhouse industry, so many growers are reducing the amount of fertilizer applied to their crops before regulations are implemented. As excess nutrients do not necessarily translate into higher profits for ornamental production (Cardarelli et al., 2010), this trend in greenhouse production might seem appropriate. However, since consumers frequently fail to fertilize their plants after the purchase, lower fertilization rates during production may result in reduced consumer performance due to the lack of nutrients provided in the container at the point of sale.

In this study, different fertilizer delivery strategies were assessed for their potential improvement of consumer performance for petunias. The fertilizer delivery strategies used included constant liquid fertilization (CLF), controlled-release fertilization (CRF), and pulse fertilization (PF) treatments. Constant liquid fertilization is the standard industry practice for greenhouse production, while CRF and PF provide alternative approaches. Controlled-release fertilizer refers to a fertilizer designed to gradually deliver nutrients to plants and is most often used in outdoor production where CLF is not practical (Medina et al., 2008; Tian and Saigusa, 2002). Pulse fertilization refers to a one-time fertilizer application made prior to placing the plants into a post-production environment and at a much higher rate than the CLF rates. Both the CRF and PF methods have a potential advantage of providing nutrients to the plant after the greenhouse production phase and thus improving post-production performance compared to the conventional CLF method. The objective of this research was to evaluate the effect of CLF, CRF, and PF during

greenhouse production on petunia growth and flowering in the production and the post-production environments.

Materials and Methods

General procedures. Plug seedlings (288 cells/flat) of petunia (*Petunia ×hybrida* Hort. Vilm.-Andr. 'Pretty Grand Red') were obtained from a commercial grower. Seedlings were transplanted into 6-pack, plastic containers (6 cells/container, 175 mL/cell), filled with a growing media (Fafard 3B custom mixed without a fertilizer starter charge; Sun Gro Horticulture, Anderson, S.Car.), and grown in a glass greenhouse at Clemson University. The medium was watered thoroughly with clear water after transplanting. Two replications of the experiment were conducted in two consecutive growing seasons: spring and fall of 2018.

The experiment was divided into two phases. The first phase simulated greenhouse production from transplant to a marketable tray comprised of flowering plants. The greenhouse phase was completed when 80% of the flowers in the tray had at least one open flower which occurred 20 days after transplant (DAT) for the first replication and 31 DAT for the second replication. Air temperature averaged 22.7±1.2 ℃ or 22.3±1.8 ℃ and daily light integral averaged 23.7±4.7 $mol \cdot m^{-2} \cdot d^{-1}$ or 13.2±3.5 $mol \cdot m^{-2} \cdot d^{-1}$, for replication 1 and 2 respectively. Once the plants were flowering, they were placed in the dark at 22 ℃ for two days to simulate a shipping environment and then placed in a greenhouse under a 50% light transmission shade curtain for one week to simulate a retail garden center environment. The temperature during the simulated retail environment averaged 24.7±0.7 ℃ or 19.8±0.2 ℃ for replication 1 and 2, respectively. Then, the plants were transplanted into 0.15-m-

diameter (0.001 m^3) containers (one plant per container and 0.15-m spacing between the containers), using the same media as above, and grown in a greenhouse which will be referred to as the post-production phase. This phase was meant to simulate the consumer environment and consequently the plants received no additional fertilizer. The post-production phase lasted for 30 or 24 days for replication 1 and 2, respectively. Air temperature averaged 25.3±1.0°C and daily light integral averaged 23.5±4.2 $mol \cdot m^{-2} \cdot d^{-1}$ for the first replication and 19.5±0.3 °C and 8.5±3.5 $mol \cdot m^{-2} \cdot d^{-1}$ for the second replication of the post-production phase.

Fertigation treatments. Plants were fertigated throughout the greenhouse production phase with a CLF solution, using 17N–2.2P–14.1K–3Ca–1Mg (4.9% ammonium-N, 12.1% nitrate-N) (Plantex Solutions, Master Plant Prod Inc., Brampton, Ont., Canada). Micronutrient concentrations were adjusted using Greencare Water-Soluble Micronutrient Blend (7% Fe, 3.5% Mn, 3.5% Zn, 1.75% B, 1.75% Cu and 0.7% Mo) (Blackmore Co., Belleville, Mich.) so that all treatments received 1 ppm Fe with each fertigation application. All 6-packs containers were fertigated manually as needed until they reached 80% of container capacity in order to minimize leaching of nutrients from the container. Container capacity was measured to be 103 mL/cell prior to the start of the experiment. The plants were fertigated as needed, and the volume of fertilizer solution applied at each irrigation was recorded for each 6-pack container.

For the CRF treatments, microprills were incorporated in the growing medium prior to planting using 16N–2.2P–9.1K–0Ca–1.2Mg Max (3-4 months release duration, 8.5% ammonium-N, 7.5% nitrate-N) (Florikan, Saratosa, Fl.). Incorporation rates were 0, 2.4,

and 4.7 $kg \cdot m^{-3}$ which represent the medium and high label rates. At flowering, the plants received pulse fertilization (PF) treatments that consisted of a one-time fertilizer application at 0, 300, or 600 $mg \cdot L^{-1}$ N made 48 h prior to placing the plants into the simulated shipping environment. The PF treatment was applied using the same fertilizer product as for the CLF treatments and at a volume of 87 mL/cell. No additional fertilizer was applied following the PF treatment and throughout the remainder of the experiment, and the growing media used in the post-production consumer phase lacked a fertilizer starter charge.

Data collection. Chlorophyll content of the petunia leaves was estimated weekly with an Apogee Chlorophyll Meter (Apogee Instruments Inc., Logan, Ut.), two leaves per treatment. The leaves sampled were the largest uppermost leaves that would fit in the meter. Media pH and electrical conductivity (EC) were measured weekly, two plants per treatment. Media EC was obtained using the 1:2 (growth medium: deionized water, v/v) method by adding 100 mL of deionized water to a 50 mL sample. Media pH and EC were measured using an Oakton PC 700 pH/conductivity meter (Cole-Parmer Instrument Company, Vernon Hills, Ill.). The date of the first open flower was recorded for each plant during the production phase (20 or 31 DAT). During the experiment, two destructive harvests were performed, one at the end of the production phase (20 or 31 DAT) and another at the end of the post-production phase (62 or 67 DAT). Plant height and number of flowers per plant were measured at each harvest, three plants per treatment at the end of the production phase and four plants per treatment at the end of the post-production phase. Plant height was determined as the distance from the surface of the medium to the base of the calyx of the

uppermost flower. Tissue nutrient analysis was performed on the entire shoot of plants harvested at the end of greenhouse and consumer phases. Dried shoot tissues (leaf, stem, and flowers) were ground and analyzed for the following nutrients: N, P, K, Ca, Mg, S, and Fe, at the USDA-ARS Laboratory (Toledo, Oh.). For the second replication, media nutrient analysis was performed in addition to the tissue analysis. For the first replication, shoot fresh weight was measured along with these two harvests. For the second replication, leaf area and root fresh weight were measured in addition to the shoot fresh weight. Two plants were measured per treatment at each data collection date. Leaf area was measured with LI-3100 Area Meter (LI-COR Inc., Lincoln, Neb.).

Experimental design and data analysis. The fertilizer treatments applied to the plants were defined by a 4×3×3 factorial combination of four CLF concentrations (0, 50, 100, or 200 $mg \cdot L^{-1}$ N), three CRF concentrations (0, 2.4, or 4.7 $kg \cdot m^{-3}$), and three PF concentrations (0, 300, or 600 $mg \cdot L^{-1}$ N). The experimental design was a completely randomized design, with four or five containers (6 cells/container) total per treatment for replication one and two, respectively. Among these, 6 plants per treatment were used for collecting weekly media pH/EC data during the production phase (3 weeks, 2 plants/week). Two plants per treatment were used for the first destructive harvest, and another two plants per treatment were used for the tissue/media nutrient analysis. Four plants per treatment were transplanted for the post-production phase, one plant per container. Among these, two plants per treatment were used for the second destructive harvest, and another two plants per treatment were used for the tissue/media nutrient analysis. Data were analyzed using

ANOVA with Student's *t* mean separation test or Tukey's HSD using JMP Pro 13. Correlations with $P < 0.05$ were considered to be statistically significant.

Results

Growth, defined as plant height, shoot fresh weight, and leaf area, and development, defined as flower number, followed a similar pattern in response to CLF and CRF at the end of the production phase (Table 3.1). In general, growth and development responded to the interaction of CLF and CRF, that is, growth and development increased as CLF increased but that increase occurred at a decreasing rate as CRF increased. For example, at low CLF, applying a CRF resulted in a large increase in growth and development, but at high CLF, the response to CRF was rather small or non-significant. More specifically, shoot fresh weight increased from 1.2 to 15.0 g with the increase of CLF from 0 to 200 $mg \cdot L^{-1}$ N when no CRF was applied, while shoot fresh weight increased from 11.5 to 16.6 g with the increase of CLF from 0 to 200 $mg \cdot L^{-1}$ N when CRF was applied at the high rate (4.7 $kg \cdot m^{-3}$).

The standard industry fertilization practice for petunia production is 100 $mg \cdot L^{-1}$ N CLF with 0 $kg \cdot m^{-3}$ CRF, so this treatment is used as a reference point to compare treatment effects. When using the industry standard CLF rate, increasing CRF to 2.4 $kg \cdot m^{-3}$ resulted in a 60% increase in flower number, but there was no further increase with the 4.7 $kg \cdot m^{-3}$ CRF rate. For leaf area, the treatment with 0 $mg \cdot L^{-1}$ N CLF with 2.4 $kg \cdot m^{-3}$ CRF resulted in the same leaf area as the industry standard. Without CRF, chlorophyll measurements

Table 3.1. Plant growth and development measurements recorded at the end of the production phase (20 or 31 days after transplant for Rep. 1 and 2 respectively). Leaf area data are from Rep. 2 while the other data are the means of Rep. 1 and 2.

Constant liquid fertilization rate ($mg \cdot L^{-1}$ N)	Controlled release fertilization rate ($kg \cdot m^{-3}$)			CLF average	ANOVA	
	0	2.4	4.7		Source	Significance
		Flower number[z]				
0	1.0 h[y]	4.9 e	5.3 de	3.7 C	CLF	***
50	2.8 g	5.3 de	6.6 ab	4.9 B	CRF	***
100	3.8 f	6.1 bc	6.0 bcd	5.3 B	CLF × CRF	***
200	5.6 cde	6.2 bc	7.1 a	6.3 A		
CRF average	3.3 C	5.6 B	6.2 A			
		Plant height (cm)[x]				
0	2.3 f	9.2 c	9.5 bc	7.0 C	CLF	***
50	5.3 e	9.7 bc	10.2 ab	8.4 B	CRF	***
100	7.7 d	10.7 a	10.6 a	9.7 A	CLF × CRF	***
200	9.3 bc	10.8 a	10.1 abc	10.1 A		
CRF average	6.1 B	10.1 A	10.1 A			
		Shoot fresh weight (g)[w]				
0	1.2 f	9.8 de	11.5 cde	7.5 C	CLF	***
50	4.3 f	13.0 bcd	15.2 ab	10.8 B	CRF	***
100	8.0 e	14.9 abc	15.2 ab	12.7 B	CLF × CRF	**
200	15.0 abc	15.4 ab	16.6 a	15.6 A		
CRF average	7.1 B	13.3 A	14.6 A			
		Leaf area (cm^2)[v]				
0	15	197	219	143 D	CLF	***
50	69	255	315	213 C	CRF	***
100	159	331	318	283 B	CLF × CRF	NS
200	349	347	386	361 A		
CRF average	148 B	282 A	320 A			
		Chlorophyll ($\mu mol \cdot m^{-2}$)[u]				
0	10.6 d	26.7 ab	27.7 ab	21.6 A	CLF	NS
50	20.8 bc	30.6 a	26.4 ab	25.9 A	CRF	***
100	25.1 ab	22.7 b	21.2 bc	23.0 A	CLF × CRF	**
200	14.9 cd	24.4 ab	31.0 a	23.4 A		
CRF average	17.8 B	26.1 A	26.6 A			

[z] The number of flowers per plant was recorded including both alive and dead flowers, and any buds developed to the point of showing flower color. n=6

[y] Means within columns having different letters are significantly different according to Student's *t*, $P < 0.05$.

[x] The distance from the surface of the medium to the base of the calyx of the uppermost flower. n=6

[w] n=4

[v] n=2

[u] n=4

NS, **, *** Non-significant or significant at $P < 0.01$ or 0.001.

increased as CLF increased from 0 to 100 $mg \cdot L^{-1}$ N, but then decreased at 200 $mg \cdot L^{-1}$ N. When CRF was added, all chlorophyll readings were similar across all CLF treatments, there was a 46% increase in chlorophyll as CRF increased from 0 to 2.4 $kg \cdot m^{-3}$, but there was no further increase with the 4.7 $kg \cdot m^{-3}$ CRF application rate.

Following the greenhouse production phase, no additional fertilization was provided to the plants in the post-production consumer phase; however, the responses of petunia growth and flowering to the CLF and CRF treatments continued to be significantly different at the end of the post-production phase. Statistical analyses are presented in Table 3.2. All growth and development parameters continued to display an interactive response to CLF and CRF, i.e., growth and development increased as CLF increased, but the addition of CRF resulted in the increase occurring at a declining rate (Fig. 3.1 and 3.2). The PF treatment applied at the end of the greenhouse production phase influenced plant growth and development in the post-production phase. For example, across all CLF and CRF treatments, leaf area increased from 466 to 540 cm^2 as PF increased from 0 to 300 $mg \cdot L^{-1}$ N, and leaf area increased further to 631 cm^2 as PF increased from 300 to 600 $mg \cdot L^{-1}$ N (Fig. 3.2. D-F). For the shoot fresh weight and plant height, the response to PF primarily occurred between 0 and 300 $mg \cdot L^{-1}$ N, and no significant change occurred at 600 $mg \cdot L^{-1}$ N (Fig. 3.2. A-C). Chlorophyll measurements at the end of the post-production phase showed that the 0 CLF and 0 CRF treatment resulted in the lowest chlorophyll value while all other treatments exhibited similar chlorophyll measurements (Fig. 3.3). For flowering, low CLF and no CRF delayed flowering by 1-2 days, but other treatments all flowered within one-day range (data not shown). The total amount of N applied through CLF during the

Table 3.2 Statistical analysis for petunia growth and development parameters at the end of the post-production phase.

	CLF	CRF	PF	CLF×CRF	CLF×PF	CRF×PF	CLF×CRF×PF
Flower number	***	***	***	***	NS	NS	NS
Plant height	***	***	***	***	NS	NS	NS
Shoot fresh weight	***	***	***	***	NS	NS	NS
Leaf area	***	***	***	**	NS	NS	NS
Chlorophyll	***	***	NS	***	NS	NS	NS
Plant fullness	***	***	***	***	NS	NS	**
Root fresh weight	***	*	***	***	NS	MS	**
Root to shoot ratio	***	***	***	***	***	***	***

CLF refers to constant liquid fertilization, CRF refers to controlled release fertilization, and PF refers to pulse fertilization.

NS, *, **, *** Non-significant or significant at $P < 0.05$, 0.01, or 0.001

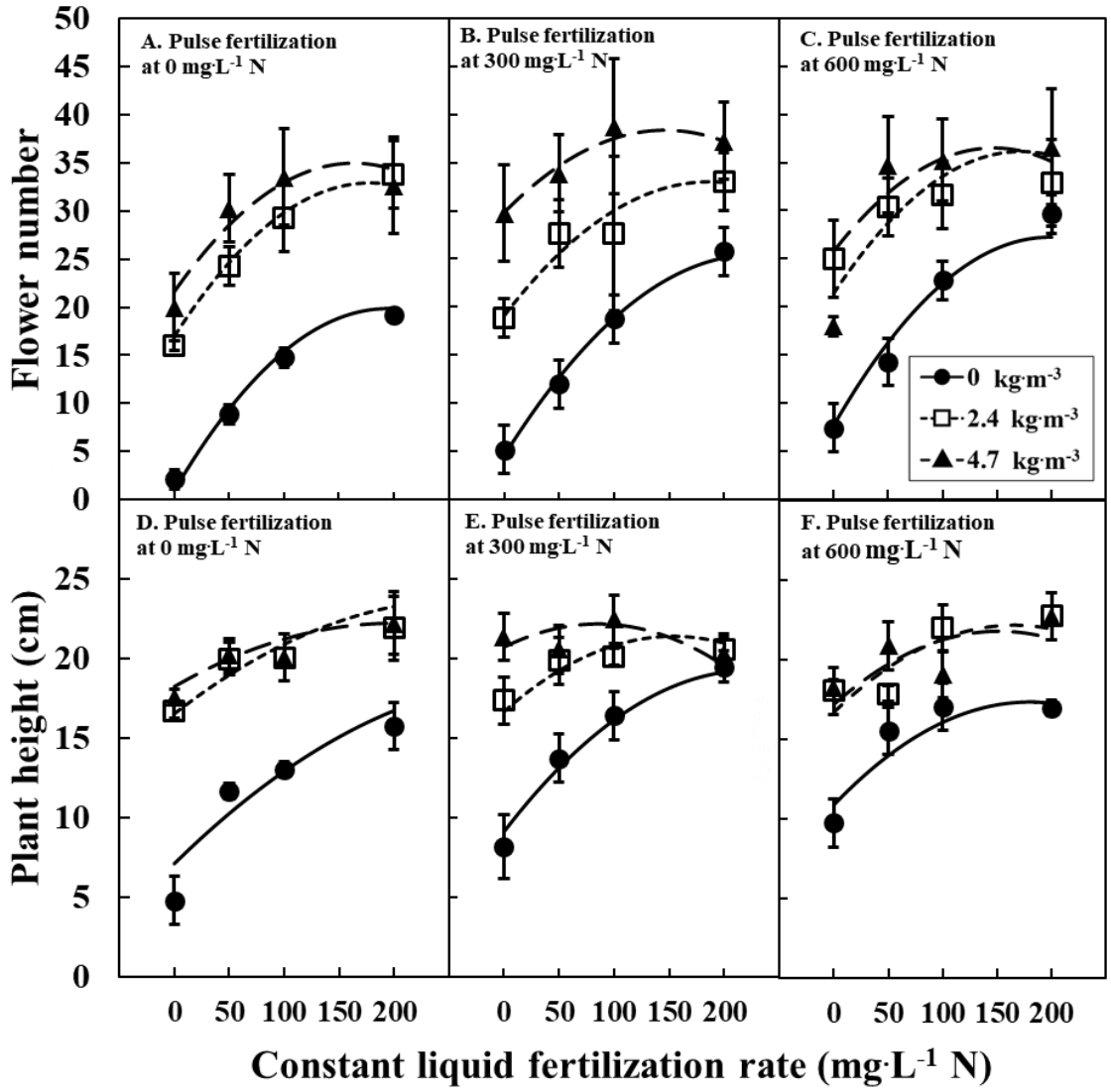

Fig. 3.1. Flower number (A-C) and plant height (D-F) recorded at the end of the post-production phase (62 or 67 days after transplant). Plants were treated with 0, 50, 100, or 200 mg·L^{-1} N constant liquid fertilization rates, 0, 2.4, or 4.7 kg·m^{-3} controlled release fertilization rates, and 0, 300, or 600 mg·L^{-1} N pulse fertilization rates. Lines indicate significant quadratic effects; $P < 0.05$ (n=8). Error bars represent ±1 SE.

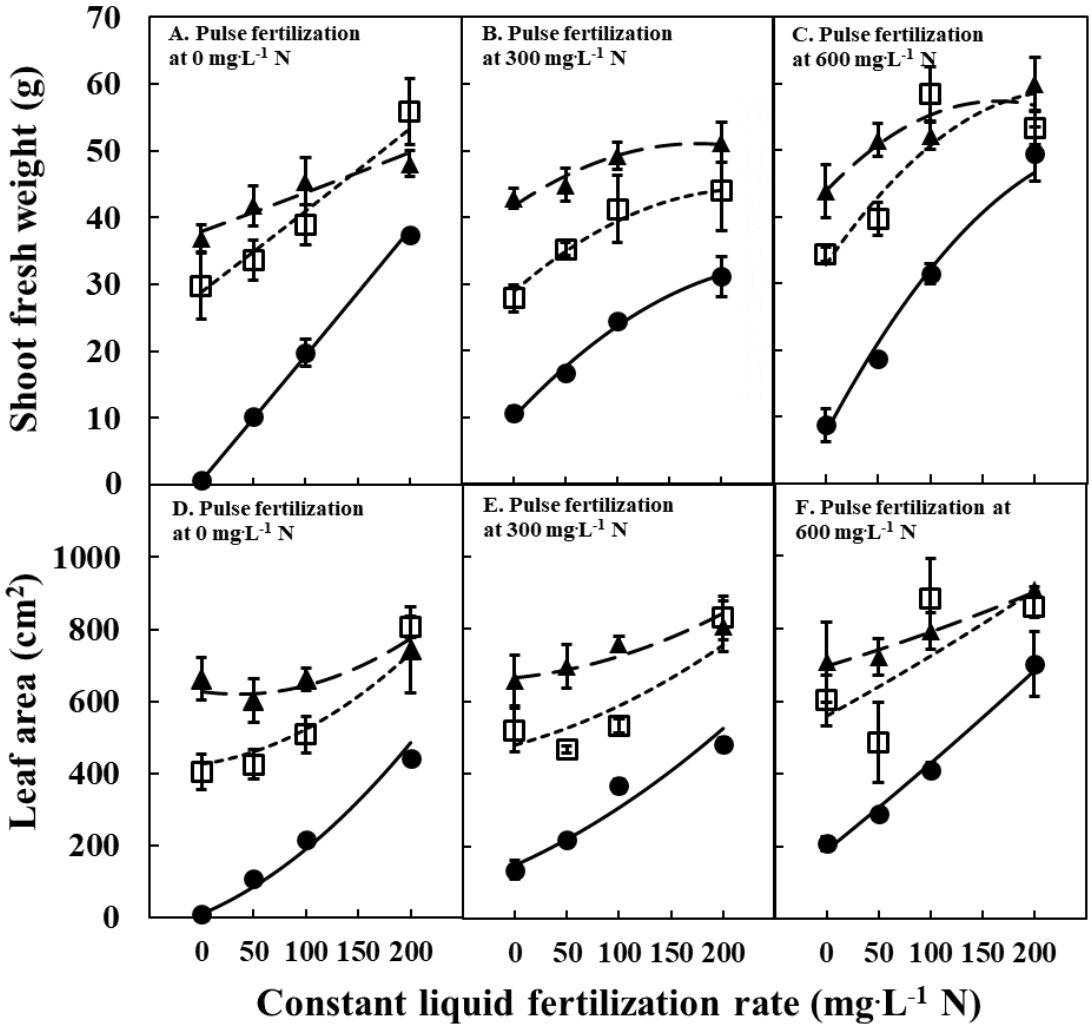

Fig. 3.2. Shoot fresh weight (A-C) and leaf area (D-F) recorded at the end of the post-production phase (62 or 67 days after transplant). Plants were treated with 0, 50, 100, or 200 mg·L^{-1} N constant liquid fertilization rates, 0, 2.4, or 4.7 kg·m^{-3} controlled release fertilization rates, and 0, 300, or 600 mg·L^{-1} N pulse fertilization rates. Leaf area data from Rep. 2 while the other data are the means of Rep. 1&2. Lines indicate significant linear or quadratic effects; $P < 0.05$ (n=6 for shoot fresh weight, 2 for leaf area). Error bars represent ±1 SE.

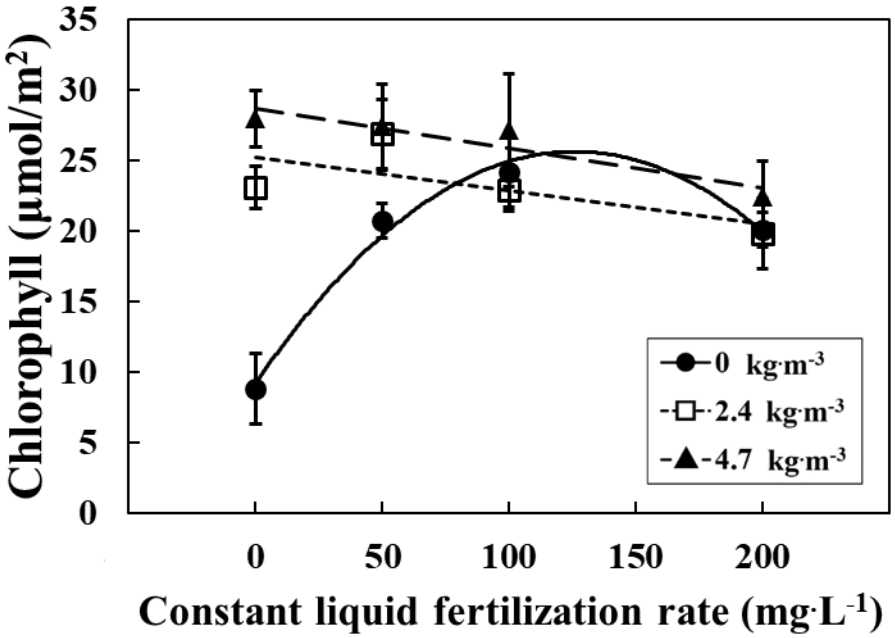

Fig. 3.3. Chlorophyll recorded at the end of the post-production phase (62 or 67 days after transplant). Plants were treated with 0, 50, 100, or 200 $mg \cdot L^{-1}$ N constant liquid fertilization rates, 0, 2.4, or 4.7 $kg \cdot m^{-3}$ controlled release fertilization rates, and 0, 300, or 600 $mg \cdot L^{-1}$ N pulse fertilization rates. Lines indicate significant linear or quadratic effects; $P < 0.05$ (n=4). Error bars represent ±1 SE. Pulse fertilization was not significant.

production phase averaged 8, 16, or 32 mg/plant for each of the 50, 100, or 200 $mg \cdot L^{-1}$ N treatments for replication 1.Plant fullness, defined as shoot fresh weight divided by plant height, increased with increasing CLF, CRF, and PF (Fig. 3.4). At the end of the post-production phase, the maximum fullness was observed at 100 $mg \cdot L^{-1}$ N CLF with 4.7 $kg \cdot m^{-3}$ CRF and 600 $mg \cdot L^{-1}$ N PF, and fullness more than doubled compared with the industry standard treatment.

At the end of the production phase, media EC increased from 0.07 to 0.68 $dS \cdot m^{-1}$ as CRF increased from 0 to 4.7 $kg \cdot m^{-3}$, while media pH decreased from 6.4 to 5.6 as CRF increased from 0 to 4.7 $kg \cdot m^{-3}$. Media EC (0.04 $dS \cdot m^{-1}$) and pH (5.5) at the end of the post-production phase were not significantly different amongst the treatments.

Root fresh weight was not significantly affected by any of the treatments at the end of the production phase (data not shown). However, at the end of the consumer phase, root fresh weight increased as CLF increased (Fig. 3.5). High CRF (4.7 $kg \cdot m^{-3}$) reduced root fresh weight, whereas high PF (600 $mg \cdot L^{-1}$ N) increased root fresh weight.

Root to shoot ratio at the end of the production phase decreased as CLF increased when there was no CRF (Fig. 3.6). When CRF was included, root to shoot ratio remained low across all CLF rates, the average ratio ranging from 0.04 to 0.08. At the end of the post-production consumer phase, the ratio decreased as CLF increased, only when there were no CRF and no PF (Fig. 3.7). The average ratio ranged from 0.1 to 0.7. When CRF and PF were added, root to shoot ratio remained low and was negatively correlated with CRF rates, the average ratio ranging from 0.03 to 0.2.

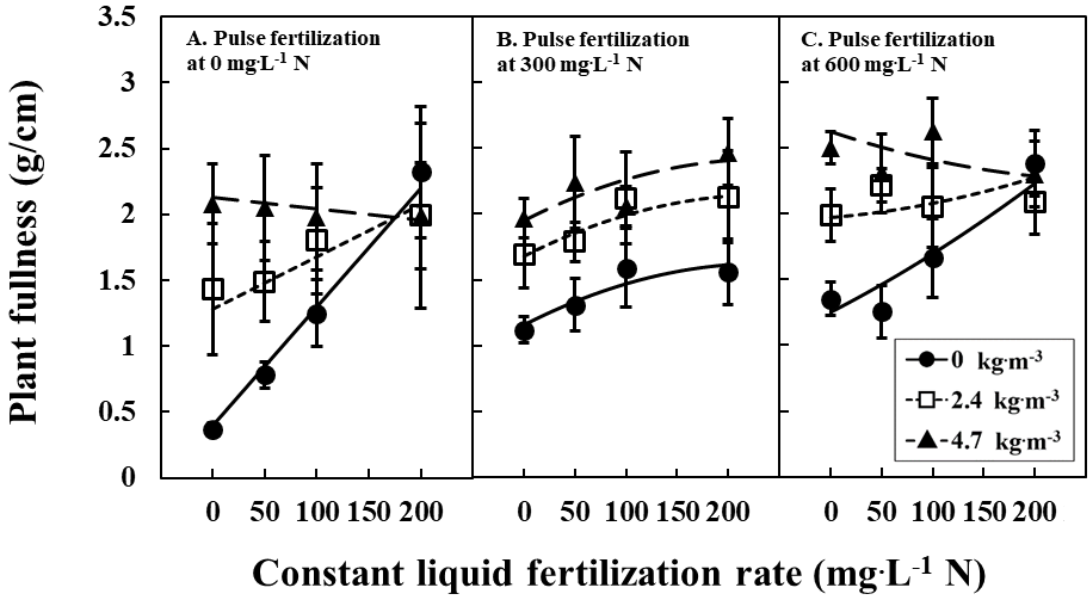

Fig. 3.4. Plant fullness (shoot fresh weight/plant height) (A-C) recorded at the end of the post-production phase (62 or 67 days after transplant). Plants were treated with 0, 50, 100, or 200 $mg \cdot L^{-1}$ N constant liquid fertilization rates, 0, 2.4, or 4.7 $kg \cdot m^{-3}$ controlled release fertilization rates, and 0, 300, or 600 $mg \cdot L^{-1}$ N pulse fertilization rates. Lines indicate significant linear or quadratic effects; $P < 0.05$ (n=6). Error bars represent ±1 SE.

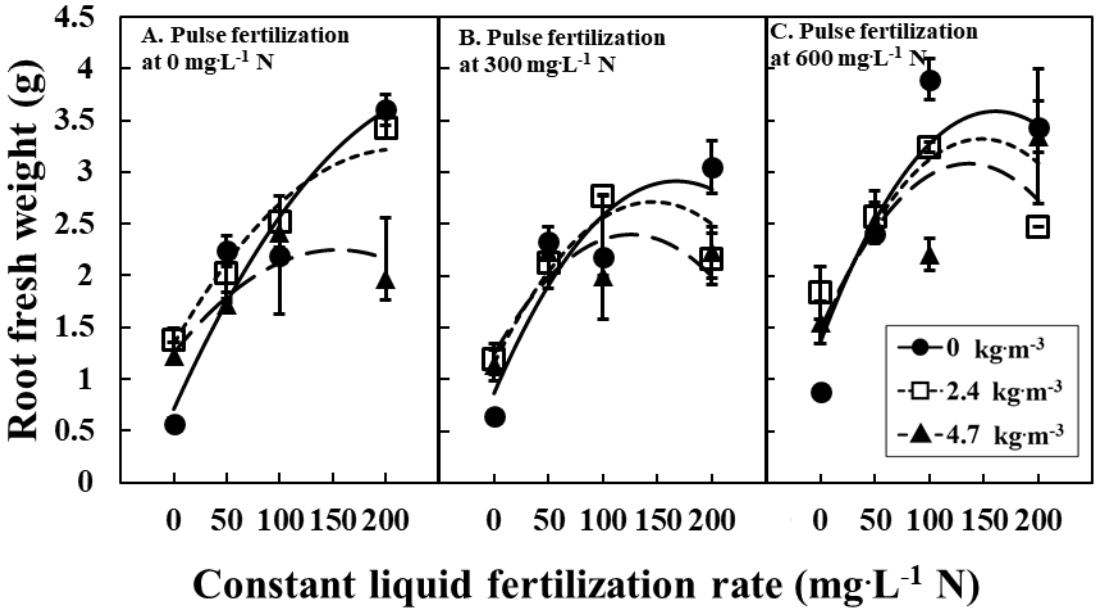

Fig. 3.5. Root fresh weight (A-C) recorded at the end of the post-production phase (67 days after transplant). Plants were treated with 0, 50, 100, or 200 mg·L^{-1} N constant liquid fertilization rates, 0, 2.4, or 4.7 kg·m^{-3} controlled release fertilization rates, and 0, 300, or 600 mg·L^{-1} N pulse fertilization rates. This data is from Rep. 2. Lines indicate significant quadratic effects; $P < 0.05$ (n=2). Error bars represent ±1 SE.

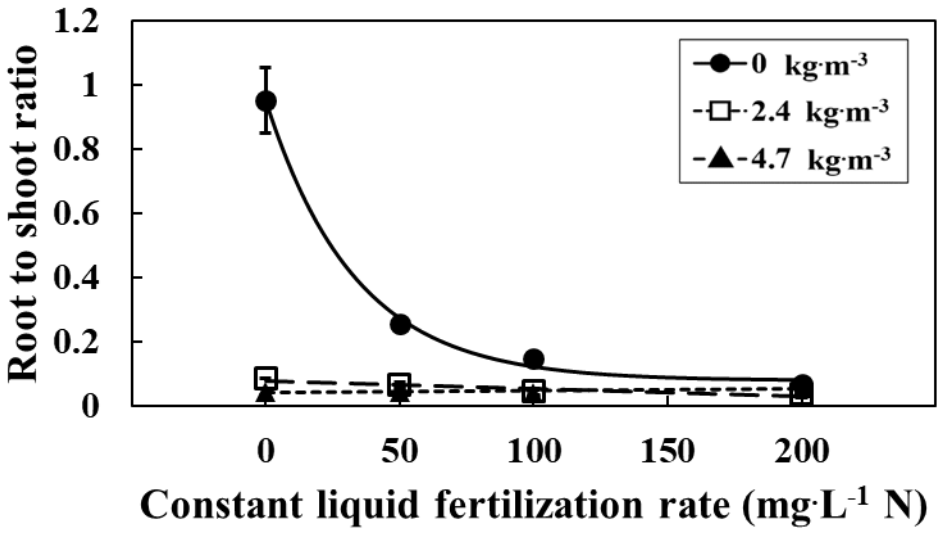

Fig. 3.6. Root to shoot ratio recorded at the end of the production phase (31 days after transplant). Plants were treated with 0, 50, 100, or 200 $mg \cdot L^{-1}$ N constant liquid fertilization rates and 0, 2.4, or 4.7 $kg \cdot m^{-3}$ controlled release fertilization rates. This data is from Rep. 2. Lines indicate significant linear or quadratic effects; $P < 0.05$ (n=2). Error bars represent ±1 SE.

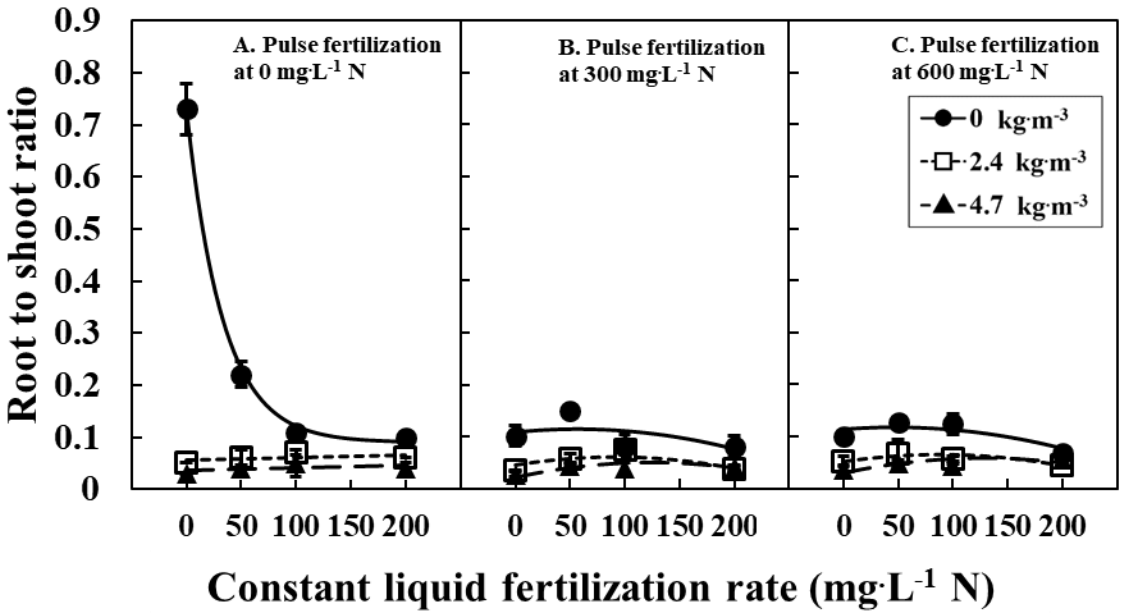

Fig. 3.7. Root to shoot ratio (A-C) recorded at the end of the post-production phase (67 days after transplant). Plants were treated with 0, 50, 100, or 200 mg·L^{-1} N constant liquid fertilization rates, 0, 2.4, or 4.7 kg·m^{-3} controlled release fertilization rates, and 0, 300, or 600 mg·L^{-1} N pulse fertilization rates. This data is from Rep. 2. Lines indicate significant linear or quadratic effects; $P < 0.05$ (n=2). Error bars represent ±1 SE.

For replication 2, the experiment lasted an additional 11 d, so the N applied was 17, 34, or 73 mg/plant for each of the 50, 100, or 200 $mg \cdot L^{-1}$ N treatments. For the 2.4 and 4.7 $kg \cdot m^{-3}$ CRF treatments, 34 or 68 mg/plant N was incorporated into the growing medium, respectively. For the 300 and 600 $mg \cdot L^{-1}$ N PF treatments, 27 or 54 mg/plant of N was applied during the single PF event, respectively.

Discussion

Petunia growth and development responses to CLF and CRF at the end of the production phase showed a typical saturation response, where the rate of increase in plant growth declines with the increasing fertilizer supply. This can be explained by the plant tissue nutrient analysis results (Table 3.3). These results exhibited a similar trend with petunia growth and development, that was, tissue N increased as CLF increased, but it increased at a decreasing rate as CRF increased. For instance, when petunias were fertilized with 100 $mg \cdot L^{-1}$ N CLF, there was a significant increase in tissue N from 5.0% of the dry weight to 6.2% as CRF increased from 0 to 2.4 $kg \cdot m^{-3}$. However, there was only a slight increase to 6.5% as CRF further increased to 4.7 $kg \cdot m^{-3}$. This demonstrates that petunia growth is closely related to tissue N. According to the nutrient analysis results, tissue P and K also showed a similar pattern, and tissue S increased with increasing CRF, probably because CLF source lacked S. Media nutrient analysis at the end of the production phase showed an increase in N as CRF increased, but CLF effect was non-significant, and there was a same pattern with media P, K, and S (Table 3.4). This demonstrates that higher CRF treatments still had nutrient reserve in the media, while most of the nutrients provided through CLF have been already absorbed by the plants.

Table 3.3. Tissue nutrient analysis measured at the end of the production phase. CLF refers to constant liquid fertilization rates and CRF refers to controlled release fertilization rates. (Rep 1&2)

CLF ($mg \cdot L^{-1}$ N)	CRF ($kg \cdot m^{-3}$)	(% dry weight)						($mg \cdot kg^{-1}$)
		N	P	K	Ca	Mg	S	Fe
0	**0**	2.1 e	0.12 e	2.3 f	1.1 a	0.9 a	0.29 de	173 a
0	**2.4**	5.4 bc	0.46 cd	3.3 ef	1.0 a	1.1 a	0.42 abc	123 a
0	**4.7**	6.3 ab	0.69 ab	4.8 de	1.1 a	1.1 a	0.47 a	151 a
50	**0**	3.8 d	0.40 d	3.9 def	1.1 a	1.1 a	0.36 bcd	101 a
50	**2.4**	6.3 ab	0.60 abc	4.4 de	1.0 a	1.1 a	0.49 a	208 a
50	**4.7**	6.7 a	0.68 ab	4.8 de	1.1 a	1.2 a	0.42 abc	196 a
100	**0**	5.0 c	0.57 bc	4.9 cde	1.1 a	1.2 a	0.33 cde	112 a
100	**2.4**	6.2 ab	0.65 ab	5.1 bcd	1.2 a	1.3 a	0.42 abc	115 a
100	**4.7**	6.5 a	0.67 ab	5.3 bcd	1.1 a	1.2 a	0.42 abc	132 a
200	**0**	6.6 a	0.74 ab	7.1 a	0.9 a	1.0 a	0.23 e	101 a
200	**2.4**	6.8 a	0.75 a	6.7 ab	1.1 a	1.0 a	0.41 abc	132 a
200	**4.7**	6.7 a	0.76 a	6.6 abc	1.1 a	1.0 a	0.46 ab	149 a

Means within columns having different letters are significantly different according to Tukey's HSD, $P < 0.05$. (n=4)

Table 3.4. Media nutrient analysis measured at the end of the production phase. CLF refers to constant liquid fertilization rates and CRF refers to controlled release fertilization rates. (Rep 2)

CLF ($mg \cdot L^{-1}$ N)	CRF ($kg \cdot m^{-3}$)	(% dry weight)						($mg \cdot kg^{-1}$)
		N	P	K	Ca	Mg	S	Fe
0	**0**	0.7 b	0.01 b	0.02 b	3.5 a	2.0 a	0.13 d	995 b
0	**2.4**	1.0 ab	0.06 b	0.12 b	0.9 d	0.6 d	0.25 cd	1562 ab
0	**4.7**	1.5 a	0.18 ab	0.43 ab	2.3 b	1.3 ab	0.49 ab	2306 ab
50	**0**	0.7 b	0.02 b	0.02 b	2.5 ab	1.5 ab	0.13 d	938 b
50	**2.4**	1.1 ab	0.05 b	0.11 b	1.0 cd	0.6 cd	0.23 cd	1808 ab
50	**4.7**	1.5 a	0.29 a	0.66 a	2.3 b	1.3 b	0.57 a	2843 a
100	**0**	0.8 b	0.02 b	0.02 b	1.9 bcd	1.1 bcd	0.12 d	981 b
100	**2.4**	1.0 ab	0.13 ab	0.32 ab	2.2 b	1.2 bc	0.33 c	1754 ab
100	**4.7**	1.4 a	0.15 ab	0.32 ab	1.9 bc	1.1 bcd	0.35 bc	1256 b
200	**0**	0.8 b	0.03 b	0.02 b	1.6 bcd	1.0 bcd	0.12 d	1028 b
200	**2.4**	1.1 ab	0.09 b	0.16 b	1.9 bcd	1.0 bcd	0.22 cd	1069 b
200	**4.7**	1.4 a	0.13 ab	0.32 ab	2.0 b	1.1 bcd	0.31 c	1384 ab

Means within columns having different letters are significantly different according to Tukey's HSD, $P < 0.05$. (n=2)

The fertilizer saturation response observed at the end of the production phase is also consistent with previous findings in ornamental plants. Frett et al. (1985) reported that when petunias were fertilized with 0, 100, 200, or 400 $mg \cdot L^{-1}$ N, the highest growth was observed with 200 $mg \cdot L^{-1}$. Similar saturation response was also seen in the production of pansies (*Viola ×wittrockiana* Gams.) (van Iersel and Kang, 2002), ornamental pepper (*Capsicum annuum* L.) (Kang et al., 2004), and containerized crape myrtle (*Lagerstroemia indica ×fauriei*) (Cabrera, 2003; Cabrera and Devereaux, 1998).

The continuation of responses to fertilization during production occurring into the post-production consumer phase was also reported in petunias (Armitage, 1986), chrysanthemum (*Dendranthema grandiflora*) (Chau and Heinz, 2006), and red-currant coprosma (*Coprosma rhamnoides*) (Hong and Suh, 2012). When fertilizer was terminated on petunias at the visible flower bud stage, a decline in post-production longevity occurred (Armitage, 1986). In some species, a negative effect of increasing the nutrient supply during production was observed during post-production performance. For example, kalanchoe (*Kalanchoe blossfeldiana*) lasted 4 d longer in the post-production environment when fertilized with 150 $mg \cdot L^{-1}$ N compared to 600 $mg \cdot L^{-1}$ (Leonard and Nell, 2000). Similar negative responses such as increased bud or leaf drop were reported in chrysanthemum (Macz et al., 2001), New Guinea impatiens (*Impatiens walleriana* Hook.f.), pot roses (*Rosa hybrida*), and poinsettias (*Euphorbia pulcherrima*), when fertilized with 150 or 200 $mg \cdot L^{-1}$ (ter Hell and Hendriks, 1995). However, negative effects of fertilization on post-production consumer performance were not observed with this study, which might be because the treatments did not reach supra-optimal levels.

However, tissue nutrient analysis at the end of the post-production phase did not show any treatment effects (Table 3.5). For tissue N, it slightly increased with increasing CRF, but the difference was statistically non-significant. Media nutrient analysis at the end of the post-production phase also did not show any treatment effects (Table 3.6). These results suggest that the continued responses of petunia growth for different CLF and CRF treatments are residual effects, not the direct effect due to the tissue nutrient levels.

All the PF treatments significantly improved consumer performance of petunias. This suggests that a one-time fertilizer application at the end of the production phase can provide additional benefit to consumer performance. The positive correlation between N supply and chlorophyll content observed in this study is comparable to results reported by many others (Cabrera, 2003; Cabrera and Devereaux, 1998; Demotes-Mainard et al., 2008; Kang et al., 2004; Najm et al., 2012; Wang et al., 2012; Yeh et al., 200).

Decreased root to shoot ratio under increasing CLF without CRF nor PF shows a typical plant response to N. Nemali and van Iersel (2004) reported that root to shoot ratio of petunia and begonia (*Begonia semperflorens-cultorum* Hort.) decreased as fertilizer EC increased from 0.12 to 2.77 $dS \cdot m^{-1}$. Similar responses were observed with pansies (van Iersel and Kang, 2002), crape myrtle (Cabrera and Devereaux, 1998), and peace lily (*Spathiphyllum*) (Yeh et al., 2000). This phenomenon can be explained by the plant's tendency to maintain homeostasis (Cabrera and Devereaux, 1998). A nutrient limitation induces root growth and increases the root to shoot ratio (Ingestad and Ågren, 1991) due to the adjustment to an imbalance of exogeneous resources by allocating new biomass to the organs that are involved in acquiring the scarcest resources (Hermans et al., 2006). The

Table 3.5. Tissue nutrient analysis measured at the end of the post-production phase. CLF refers to constant liquid fertilization rates, CRF refers to controlled release fertilization rates, and PF refers to pulse fertilization rates. (Rep 1&2)

CLF ($mg \cdot L^{-1}$ N)	CRF ($kg \cdot m^{-3}$)	PF ($mg \cdot L^{-1}$ N)	----------(% dry weight)----------						($mg \cdot kg^{-1}$)
			N	P	K	Ca	Mg	S	Fe
0	**0**	**0**	2.8 a	0.09 c	2.7 ab	1.4 a	1.2 a	0.3 a	96 a
0	**0**	**300**	3.3 a	0.19 abc	3.5 ab	1.1 a	1.1 a	0.4 a	102 a
0	**0**	**600**	3.6 a	0.24 abc	3.6 ab	1.1 a	1.0 a	0.4 a	106 a
0	**2.4**	**0**	3.1 a	0.23 abc	1.5 b	0.9 a	1.0 a	0.4 a	88 a
0	**2.4**	**300**	3.6 a	0.29 abc	2.0 ab	0.8 a	0.8 a	0.4 a	130 a
0	**2.4**	**600**	3.6 a	0.32 abc	2.3 ab	0.9 a	0.9 a	0.5 a	126 a
0	**4.7**	**0**	4.1 a	0.40 abc	2.0 ab	1.4 a	1.3 a	0.6 a	107 a
0	**4.7**	**300**	4.1 a	0.41 abc	2.6 ab	1.2 a	1.0 a	0.6 a	134 a
0	**4.7**	**600**	3.9 a	0.50 a	3.3 ab	1.1 a	0.8 a	0.5 a	111 a
50	**0**	**0**	2.6 a	0.14 bc	2.0 ab	1.1 a	1.1 a	0.3 a	100 a
50	**0**	**300**	2.6 a	0.19 abc	2.3 ab	1.0 a	0.9 a	0.4 a	75 a
50	**0**	**600**	2.8 a	0.22 abc	2.6 ab	1.0 a	0.9 a	0.4 a	80 a
50	**2.4**	**0**	3.1 a	0.26 abc	1.8 ab	0.8 a	0.8 a	0.4 a	108 a
50	**2.4**	**300**	3.0 a	0.27 abc	1.9 ab	0.8 a	0.7 a	0.4 a	112 a
50	**2.4**	**600**	3.2 a	0.29 abc	2.0 ab	0.9 a	0.8 a	0.4 a	101 a
50	**4.7**	**0**	3.7 a	0.33 abc	1.9 ab	1.1 a	1.0 a	0.6 a	104 a
50	**4.7**	**300**	3.7 a	0.34 abc	2.1 ab	1.1 a	1.0 a	0.5 a	118 a
50	**4.7**	**600**	4.1 a	0.37 abc	2.4 ab	1.1 a	1.0 a	0.5 a	114 a
100	**0**	**0**	2.5 a	0.17 abc	1.9 ab	1.1 a	1.0 a	0.4 a	86 a
100	**0**	**300**	2.7 a	0.25 abc	2.4 ab	1.1 a	0.9 a	0.4 a	95 a
100	**0**	**600**	2.9 a	0.27 abc	2.6 ab	1.1 a	0.9 a	0.4 a	93 a
100	**2.4**	**0**	3.4 a	0.31 abc	2.1 ab	1.0 a	0.9 a	0.5 a	139 a
100	**2.4**	**300**	3.5 a	0.46 ab	3.0 ab	1.1 a	0.7 a	0.6 a	130 a
100	**2.4**	**600**	3.7 a	0.36 abc	2.5 ab	1.1 a	1.0 a	0.5 a	103 a
100	**4.7**	**0**	3.6 a	0.34 abc	2.0 ab	1.2 a	1.0 a	0.5 a	106 a
100	**4.7**	**300**	4.0 a	0.35 abc	2.2 ab	1.1 a	1.0 a	0.5 a	111 a
100	**4.7**	**600**	3.8 a	0.34 abc	2.3 ab	1.0 a	0.9 a	0.5 a	125 a
200	**0**	**0**	3.0 a	0.50 a	4.1 a	1.1 a	0.6 a	0.5 a	92 a
200	**0**	**300**	2.9 a	0.30 abc	2.5 ab	1.0 a	0.9 a	0.4 a	95 a
200	**0**	**600**	3.0 a	0.33 abc	2.8 ab	1.0 a	0.9 a	0.3 a	96 a
200	**2.4**	**0**	3.5 a	0.33 abc	2.3 ab	1.1 a	0.9 a	0.5 a	98 a
200	**2.4**	**300**	3.7 a	0.36 abc	2.7 ab	1.1 a	0.9 a	0.4 a	116 a
200	**2.4**	**600**	3.7 a	0.37 abc	2.8 ab	1.1 a	0.9 a	0.4 a	128 a
200	**4.7**	**0**	4.0 a	0.37 abc	2.5 ab	1.1 a	0.9 a	0.5 a	145 a
200	**4.7**	**300**	3.7 a	0.38 abc	2.7 ab	1.0 a	0.8 a	0.5 a	114 a
200	**4.7**	**600**	3.9 a	0.35 abc	2.6 ab	1.0 a	0.8 a	0.5 a	111 a

Means within columns having different letters are significantly different according to Tukey's HSD, $P < 0.05$. (n=4)

Table 3.6. Media nutrient analysis measured at the end of the post-production phase. CLF refers to constant liquid fertilization rates, CRF refers to controlled release fertilization rates, and PF refers to pulse fertilization rates. (Rep 2)

CLF ($mg \cdot L^{-1}$ N)	CRF ($kg \cdot m^{-3}$)	PF ($mg \cdot L^{-1}$ N)	----------(% dry weight)----------						($mg \cdot kg^{-1}$)
			N	P	K	Ca	Mg	S	Fe
0	**0**	**0**	0.7 a	0.02 a	0.02 b	1.6 a	1.0 a	0.13 a	957 a
0	**0**	**300**	0.8 a	0.02 a	0.01 b	0.8 a	0.5 a	0.13 a	812 a
0	**0**	**600**	0.8 a	0.02 a	0.02 b	0.7 a	0.5 a	0.13 a	882 a
0	**2.4**	**0**	0.8 a	0.02 a	0.01 b	0.7 a	0.4 a	0.14 a	793 a
0	**2.4**	**300**	0.8 a	0.02 a	0.01 b	0.7 a	0.4 a	0.13 a	782 a
0	**2.4**	**600**	0.8 a	0.02 a	0.01 b	0.7 a	0.4 a	0.13 a	801 a
0	**4.7**	**0**	0.8 a	0.02 a	0.02 b	0.7 a	0.5 a	0.14 a	830 a
0	**4.7**	**300**	0.7 a	0.02 a	0.02 b	0.8 a	0.5 a	0.14 a	846 a
0	**4.7**	**600**	0.8 a	0.02 a	0.02 b	0.7 a	0.5 a	0.14 a	964 a
50	**0**	**0**	0.7 a	0.02 a	0.01 b	1.3 a	0.8 a	0.13 a	857 a
50	**0**	**300**	0.7 a	0.02 a	0.01 b	0.7 a	0.4 a	0.13 a	823 a
50	**0**	**600**	0.8 a	0.02 a	0.01 b	0.7 a	0.4 a	0.13 a	871 a
50	**2.4**	**0**	0.8 a	0.02 a	0.01 b	0.8 a	0.5 a	0.14 a	857 a
50	**2.4**	**300**	0.8 a	0.02 a	0.01 b	0.7 a	0.4 a	0.13 a	844 a
50	**2.4**	**600**	0.8 a	0.02 a	0.01 b	0.7 a	0.4 a	0.13 a	794 a
50	**4.7**	**0**	0.8 a	0.02 a	0.02 b	0.6 a	0.4 a	0.14 a	859 a
50	**4.7**	**300**	0.7 a	0.02 a	0.02 b	0.6 a	0.4 a	0.13 a	733 a
50	**4.7**	**600**	0.8 a	0.02 a	0.02 b	0.7 a	0.4 a	0.12 a	893 a
100	**0**	**0**	0.6 a	0.02 a	0.01 b	2.8 a	1.6 a	0.13 a	859 a
100	**0**	**300**	0.7 a	0.02 a	0.01 b	1.3 a	0.8 a	0.13 a	962 a
100	**0**	**600**	0.7 a	0.02 a	0.01 b	0.7 a	0.4 a	0.12 a	846 a
100	**2.4**	**0**	0.8 a	0.02 a	0.02 b	0.6 a	0.3 a	0.12 a	740 a
100	**2.4**	**300**	0.8 a	0.02 a	0.01 b	0.5 a	0.3 a	0.12 a	810 a
100	**2.4**	**600**	0.8 a	0.02 a	0.01 b	0.8 a	0.5 a	0.13 a	733 a
100	**4.7**	**0**	0.6 a	0.02 a	0.01 b	3.2 a	1.8 a	0.14 a	853 a
100	**4.7**	**300**	0.8 a	0.02 a	0.06 a	0.6 a	0.4 a	0.13 a	750 a
100	**4.7**	**600**	0.8 a	0.02 a	0.01 b	0.7 a	0.4 a	0.13 a	775 a
200	**0**	**0**	0.8 a	0.02 a	0.01 b	0.7 a	0.4 a	0.13 a	864 a
200	**0**	**300**	0.7 a	0.02 a	0.01 b	0.9 a	0.5 a	0.12 a	720 a
200	**0**	**600**	0.7 a	0.02 a	0.01 b	0.8 a	0.5 a	0.12 a	762 a
200	**2.4**	**0**	0.8 a	0.02 a	0.01 b	1.1 a	0.7 a	0.13 a	813 a
200	**2.4**	**300**	0.7 a	0.02 a	0.02 b	0.8 a	0.5 a	0.13 a	813 a
200	**2.4**	**600**	0.7 a	0.02 a	0.02 b	1.3 a	0.8 a	0.12 a	709 a
200	**4.7**	**0**	0.8 a	0.02 a	0.02 b	0.6 a	0.4 a	0.13 a	819 a
200	**4.7**	**300**	0.7 a	0.02 a	0.01 b	0.6 a	0.4 a	0.12 a	755 a
200	**4.7**	**600**	0.7 a	0.02 a	0.02 b	1.6 a	0.9 a	0.13 a	938 a

Means within columns having different letters are significantly different according to Tukey's HSD, $P < 0.05$. (n=2)

loss of the same effect with the addition of CRF and PF suggests that N is no longer a limiting factor in these treatments. Based on tissue nutrient analysis at the end of the post-production phase (Table 3.5), tissue N was the lowest when CLF was the only source of N fertilizer, implying that this N deficiency was recovered by adding CRF and PF.

As for the different quantities of fertilizer applied via the different methods, mg N applied per plant was similar for 100 $mg \cdot L^{-1}$ N CLF and 2.4 $kg \cdot m^{-3}$ CRF, and also for 200 $mg \cdot L^{-1}$ N CLF and 4.7 $kg \cdot m^{-3}$ CRF. Petunias treated with 0 CLF with 2.4 $kg \cdot m^{-3}$ CRF resulted in the same leaf area as the 100 $mg \cdot L^{-1}$ N CLF with 0 CRF, suggesting two different methods of delivering the same amount of nutrients to the plant.

Overall, the industry standard fertilization rate (100 $mg \cdot L^{-1}$ N CLF without CRF or PF) produced the lowest acceptable petunia plants since there was a significant negative consequences on the petunia growth and development below this rate, and as fertilization was increased either through CRF or PF, there was a significantly more growth of petunias. Using less or just enough fertilizers may be beneficial for the growers and environment, but not for the consumers. Therefore, one of the biggest challenges in petunia production industry would be using just enough fertilization to achieve improved consumer performance without any negative impacts. Based on our findings, there are two possible suggestions. First, using 50 $mg \cdot L^{-1}$ N CLF with 2.4 $kg \cdot m^{-3}$ CRF. This method makes use of growth restriction benefit of the low CLF, at the same time improving consumer performance by incorporating CRF for longer fertilizer release duration. The second method is using 100 $mg \cdot L^{-1}$ CLF with 300 $mg \cdot L^{-1}$ N PF. With this method, improved consumer performance can be achieved without the need to change production method very

much, since plants already receive irrigation just before shipping. The only difference will be including PF with this last irrigation.

Conclusions

The objective of this research was to examine the efficacy of alternative fertilizer delivery strategies, CRF and PF, on enhancing consumer performance of petunias. The results showed that both CRF and PF had positive effects on the finished product quality as well as the post-production consumer performance. By applying CRF and/or PF, all the growth and development parameters increased, including plant height, shoot fresh weight, leaf area, and flower number. Application of CRF exhibited the added benefit of increased foliar greenness and slightly faster flowering. The only negative effect observed was what might be considered to be excessive growth in some of the treatments that might make the plant more difficult to handle during shipping. This problem can be addressed with the application plant growth regulators which will be addressed in the next chapter.

CHAPTER FOUR

FERTILIZATION AND PACLOBUTRAZOL APPLICATION DURING GREENHOUSE PRODUCTION AFFECTS PETUNIA GROWTH AND FLOWERING IN THE GREENHOUSE AS WELL AS IN THE POST-PRODUCTION ENVIRONMENT

Introduction

Annual ornamental plants produced in high density situations tend to grow taller than desired and thus benefit from the use of plant growth regulator (PGR) to reduce the rate of stem elongation. From a production viewpoint, a high-quality plant is one that is compact, well-branched, and sufficiently rigid to allow for forceful handling and dense packing on shipping carts. Paclobutrazol (*rac*-(2*R*,3*R*)-1-(4-chlorophenyl)-4,4-dimethyl-2-(1*H*-1,2,4-triazol-1-yl) pentan-3-ol) is a widely used PGR in bedding plant production (Keever and Kessler, 2008) that inhibits gibberellin synthesis within the plant which is responsible for cellular elongation (Hedden and Graebe, 1985). Besides reducing stem elongation, PGRs can promote uniform flowering, darken leaf color, decrease leaf expansion, and increase tolerance to handling stresses (Fishel, 2015, Latimer and Whipker, 2012). Plant growth regulators are most effective when applied at the appropriate times, which is just prior to rapid stem elongation. This is typically one or two weeks after transplanting a plug. Late application should be avoided, especially in the case of triazoles such as paclobutrazol, because they may delay flower opening when applied after flower initiation (Latimer and Whipker, 2012).

While paclobutrazol is a useful tool for the production of high-quality bedding plants, it is important that plants resume normal growth once moved to a consumer setting

or transplanted to the landscape (Latimer, 1991; Ruter, 1994). Residual effects of PGR may be more important with the use of the triazole compounds, such as paclobutrazol, which are metabolized slowly and can affect post-production plant performance (Keever and Kessler, 2008). The half-life of paclobutrazol in a plant or soil is in the range of several months (Rademacher, 2000). Excessive height reduction and slow growth can result from excess paclobutrazol application, and stunting can be persistent in sensitive species (Latimer and Whipker, 2012).

Plant growth regulators can be applied either as a foliar spray or a substrate drench. The benefits of drench application include a more uniform and longer-lasting effect and a less negative effect on flowering or flower size (Latimer and Whipker, 2012). In osteospermum (*Osteospermum ecklonis*), foliar sprays of ≤80 $mg \cdot L^{-1}$ paclobutrazol were ineffective in controlling plant growth, however, substrate drenches of paclobutrazol at 16 mg/pot limited plant height by 21% compared to the untreated control, and flowering was not affected (Gibson and Whipker, 2003). When potted black iris (*Iris nigricans* Dinsm.) plants were sprayed with 100, 250, 500, or 1000 $mg \cdot L^{-1}$ paclobutrazol, they resulted in curved leaves (Al-Khassawneh et al., 2006). When they were drenched with 0.25 or 1.0 $mg \cdot L^{-1}$ paclobutrazol, there was a significant reduction in plant height as well as an increase in flowering by 12% compared to untreated plants. However, substrate drenches of paclobutrazol at 2 $mg \cdot L^{-1}$ reduced flowering by 80% and excessively reduced stem elongation.

Nitrogen restriction is another method that can be used during commercial production to regulate plant growth. With increasing nitrogen application, shoot growth is

significantly favored over root growth (Cabrera and Devereaux, 1998). In petunia (*Petunia ×hybrida* Hort. Vilm.-Andr.) and begonia (*Begonia semperflorens-cultorum* Hort.), root to shoot ratio decreased as fertilizer electrical conductivity increased from 0.12 to 2.77 $dS \cdot m^{-1}$ (Nemali and van Iersel, 2004). Low fertilization rates can reduce growth and lower the requirement for paclobutrazol; however, this can occur at the expense of supplying the retail customer with a plant that contains enough nutrients to sustain further growth in the consumer environment where fertilization is frequently lacking.

In this study, the interaction effects of paclobutrazol and constant liquid fertilization (CLF) rates on the greenhouse quality and post-production consumer performance of petunias were assessed. The hypothesis was that lower fertilization rates allow the use of lower rates of paclobutrazol application to achieve commercially acceptable plants, however the lower fertilization rates during production will negatively affect growth and flowering in the post-production environment. In contrast, high CLF rates will require high PGR rates to produce a high-quality flowering crop, and the high PGR rates will negatively affect growing and flowering in the post-production environment. Thus, the objective of this research was to determine the best strategy for balancing CLF rate and paclobutrazol application rate in the greenhouse environment so that growth and flowering can be maximized in the post-production consumer environment.

Materials and Methods

General procedures. Plug seedlings (288 cells/flat) of petunia (*Petunia ×hybrida* Hort. Vilm.-Andr. 'Easy Wave Pink') were obtained from a commercial grower. Four flats (1152 seedlings) were received and 960 seedlings were used. Seedlings were transplanted

into plastic containers (6 cells/container, 175 mL/cell), filled with a growing media (Fafard 3B without a starter charge; Sun Gro Horticulture, Anderson, S.Car.), and grown in a glass greenhouse. Seedlings were watered thoroughly with clear water immediately after transplanting.

The experiment was divided into two phases. The first phase simulated greenhouse production from transplant to a marketable flowering tray of bedding plants, and the second phase simulated post-production performance. The greenhouse phase was completed 38 days after transplant (DAT) for the first replication and 34 DAT for the second replication. Air temperature averaged 20.6±0.5 °C and daily light integral averaged 14.7±7.3 $mol \cdot m^{-2} \cdot d^{-1}$. Paclobutrazol was applied 7 or 10 DAT for replication 1 and 2, respectively. Flowering plants were placed in the dark at 22 °C for two days to simulate shipping and then placed in a greenhouse under a 50% light transmission shade curtain and 21.9±0.4 °C to simulate a retail environment for one week. For the post-production phase, the plants were transplanted into 3-gal. (0.011 m^3) containers (3 plants per container) and grown in a greenhouse. This phase was meant to simulate the consumer environment, and consequently the plants received no additional fertilizer. The post-production phase lasted for 30 days. Air temperature averaged 22.3±0.4 °C and daily light integral averaged 19.3±6.4 $mol \cdot m^{-2} \cdot d^{-1}$.

Fertigation and paclobutrazol treatments. The fertilizer and paclobutrazol treatments applied to the plants were defined by a factorial combination of four CLF concentrations (50, 100, 150, or 200 $mg \cdot L^{-1}$ N) and four paclobutrazol concentrations (0, 5, 10, or 20 $mg \cdot L^{-1}$ paclobutrazol). Plants were fertigated throughout the greenhouse

production phase with a CLF solution, using 15N–2.2P–12.5K–5Ca–2Mg (1.1% ammoniacal-N, 11.8% nitrate-N, and 2.1% urea-N) (Peters Excel Cal-Mag Special, ICL Fertilizers Co., Dublin, Oh.). Micronutrient concentrations were adjusted using Greencare Water-Soluble Micronutrient Blend (7% Fe, 3.5% Mn, 3.5% Zn, 1.75% B, 1.75% Cu and 0.7% Mo) (The Blackmore Company, Belleville, Mich.), so that all treatments received 1 ppm Fe with each fertigation application. All 6-pack containers were fertigated manually as needed until they reached 80% of container capacity in order to minimize leaching of nutrients from the container. On average, the plants were fertigated three times per week throughout the four-week growing period. The volume of fertilizer solution applied at each irrigation was recorded for each 6-pack container.

Paclobutrazol (Bonzi, Syngenta, Greensboro, N.Car.) was applied as a drench at 7 or 10 days after transplanting. Four different rates (0, 5, 10, or 20 $mg \cdot L^{-1}$ paclobutrazol) were applied, and the drench volume was applied at a volume of 87 mL/cell. No fertilizer was applied after the greenhouse production phase. The growing media used in the post-production consumer phase was a commercial peat-based growing media with starter charge (Fafard 3B; Sun Gro Horticulture, Anderson, S.Car.).

Data collection. Chlorophyll content of the petunia leaves was estimated weekly with an Apogee Chlorophyll Meter (Apogee Instruments Inc., Logan, Ut.). Twelve leaves were measured per treatment at each measurement date, three leaves per block. The leaves sampled were the largest uppermost leaves that would fit in the meter. Media pH and electrical conductivity were measured weekly, two plants per treatment. The electrical conductivity was measured using the 1:2 method (growing medium vol.: deionized water

vol.). The electrical conductivity and pH were measured using Oakton PC 700 pH/conductivity meter (Cole-Parmer Instrument Company, Vernon Hills, Ill.). The date of the first open flower was recorded for each plant during the production phase (38 or 34 DAT). During the experiment, two destructive harvests were performed, one at the end of the production phase and another at the end of the post-production phase (74 or 70 DAT). The following data were recorded on 12 plants per treatment for each harvest: shoot fresh weight, plant height, number of flowers per plant, and leaf area, Also, root fresh weight was recorded after the greenhouse production phase. Plant height was determined as the distance from the surface of the medium to the base of the calyx of the uppermost flower. The number of flowers per plant was recorded including both alive and dead flowers, and any buds developed to the point of showing flower petal color. Leaf area was measured with LI-3100 Area Meter (LI-COR Inc., Lincoln, Neb.).

Experimental design and data analysis. The data were analyzed using ANOVA with Student's *t* mean separation test using JMP Pro 13. Correlations with $P < 0.05$ were considered to be statistically significant. The experiment was conducted twice during the spring 2019. Experimental design was a randomized complete-block design, using proximity to the evaporative cooling pads as the block to reduce the potential effect of varying temperatures across the greenhouses due to the cooling pads. There were five containers (6 cells/container) total per treatment for each of the replications, and among these, there were two blocks (one container per block) per treatment (12 plants/treatment) for the first destructive harvest. Six plants per treatment were used for collecting weekly media pH/EC data during the production phase (3 weeks, 2 plants/week). Twelve plants

per treatment were transplanted for the post-production phase, three plant per container. Thus, there were four blocks for the post-production phase and these were used for the second destructive harvest.

Results and Discussion

Growth, defined as plant height, shoot fresh weight, and leaf area, and development, defined as flower number, followed a similar pattern in response to CLF and paclobutrazol at the end of the production phase (Fig. 4.1). Statistical analyses are presented in Table 4.1. In general, growth and development measurements increased as CLF increased but decreased as paclobutrazol increased. The standard industry fertilization practice for petunias is 100 $mg \cdot L^{-1}$ N CLF, so this treatment will be used as a reference point. When using the industry standard CLF rate, increasing paclobutrazol to 5 $mg \cdot L^{-1}$ resulted in a large (53%) decrease in plant height, but increasing paclobutrazol from 5 to 20 $mg \cdot L^{-1}$ had a relatively small (18%) additional decrease in plant height. When using a lower CLF rate than the industry standard, that is, 50 $mg \cdot L^{-1}$ N and 0 $mg \cdot L^{-1}$ paclobutrazol, height decreased 35%.

Following the greenhouse production phase, no additional fertilization was provided in the post-production phase except for the starter charge in the growing media that was used to transplant the plants. However, the CLF and paclobutrazol treatments applied during the production phase continued to affect growth and development during the post-production consumer phase (Fig. 4.2). Most of the growth and development parameters measured during the post-production phase displayed an interactive response to CLF and paclobutrazol, i.e., growth and development increased as CLF increased, but

Table 4.1. Statistical analysis for petunia growth and development parameters

		CLF	PGR	CLF×PGR
At the end of the production phase (38 or 34 days after transplant)	Plant height	***	***	***
	Shoot fresh weight	***	***	***
	Leaf area	***	***	***
	Flower number	***	***	***
	Chlorophyll	***	***	***
	Plant fullness	***	***	**
At the end of the post-production phase (74 or 70 days after transplant)	Plant height	***	***	NS
	Shoot fresh weight	***	***	NS
	Leaf area	NS	***	NS
	Flower number	***	***	***
	Chlorophyll	NS	***	*
	Plant fullness	***	NS	NS

CLF refers to constant liquid fertilization, PGR refers to plant growth regulator (paclobutrazol).

NS, *, **, *** Non-significant or significant at $P < 0.05$, 0.01, or 0.001

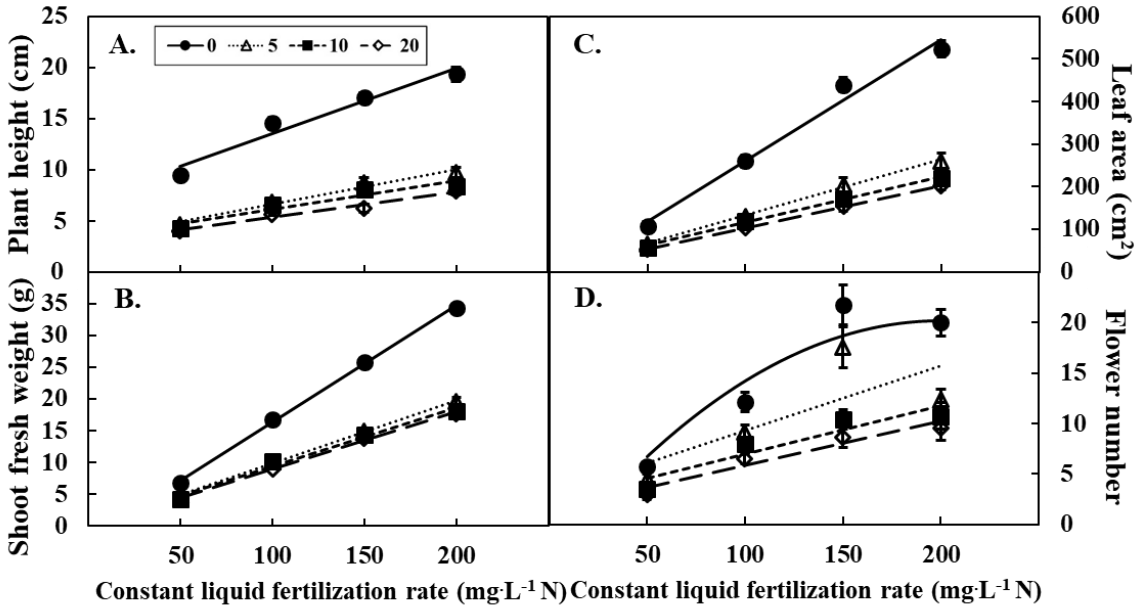

Fig. 4.1. Plant height (A), shoot fresh weight (B), leaf area (C), and flower number (D) recorded at the end of the production phase (38 or 34 days after transplant). Plants were treated with 50, 100, 150, or 200 mg·L^{-1} N constant liquid fertilization rates and 0, 5, 10, or 20 mg·L^{-1} paclobutrazol rates. Lines indicate significant linear or quadratic effects; $P < 0.05$ (n=24). Error bars represent ±1 SE.

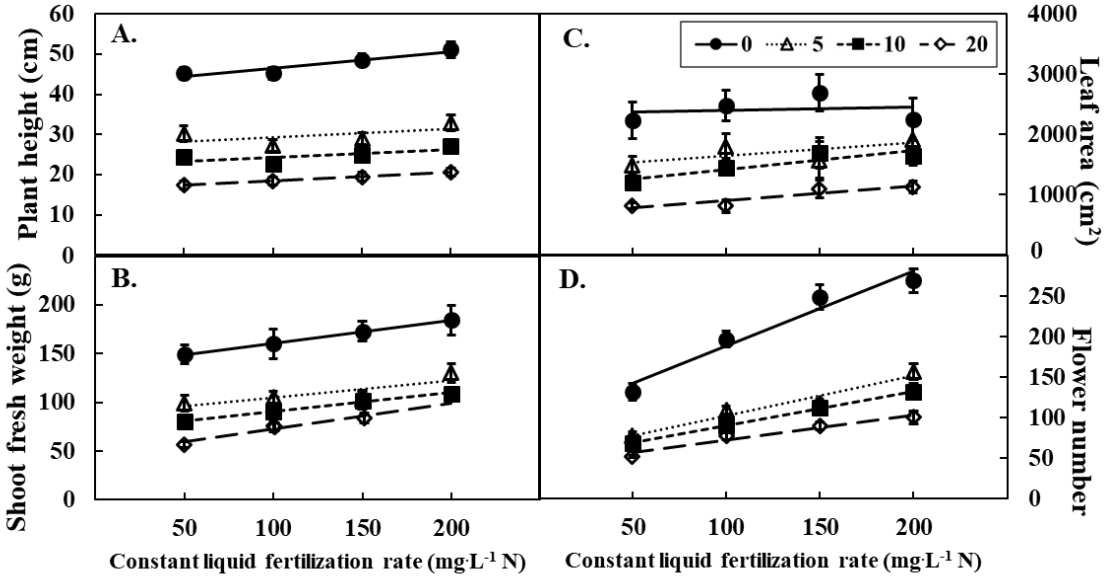

Fig. 4.2. Plant height (A), shoot fresh weight (B), leaf area (C), and flower number (D) recorded at the end of the post-production phase (74 or 70 days after transplant). Plants were treated with 50, 100, 150, or 200 mg·L^{-1} N constant liquid fertilization rates and 0, 5, 10, or 20 mg·L^{-1} paclobutrazol rates. Lines indicate significant linear or quadratic effects; $P < 0.05$ (n=24). Error bars represent ±1 SE.

decreased as paclobutrazol increased. For plant height, effect of CLF was evened out compared to the data at the end of the production phase, but the effect of paclobutrazol continued to be highly significant. For instance, across all CLF treatments, plant height decreased 60% as paclobutrazol increased from 0 to 20 $mg \cdot L^{-1}$. Flower number continued to display a significant effect of CLF and paclobutrazol at the end of the post-production phase. Compared with the industry standard treatment, flower number increased 72% as CLF increased from 100 to 200 $mg \cdot L^{-1}$ N, but it decreased by 45% as paclobutrazol increased from 0 to 5 $mg \cdot L^{-1}$.

Petunia growth and flowering at the end of the production as well as the post-production consumer phase increased as CLF increased, but decreased as paclobutrazol increased. The effect of fertilization on petunia growth was also reported by Klock-Moore and Broschat (1999), who found that shoot dry mass more than doubled as fertilizer concentration increased from 100 to 200 $mg \cdot L^{-1}$ N.

When paclobutrazol was added, petunias exhibited greener leaves with increasing CLF and paclobutrazol, but the leaf greenness decreased at 200 $mg \cdot L^{-1}$ N CLF at the end of the production phase (Fig. 4.3A). For 0 paclobutrazol treatments, chlorophyll decreased linearly as CLF increased. For 100 $mg \cdot L^{-1}$ N CLF treatments, chlorophyll increased 94% as paclobutrazol increased from 0 to 10 $mg \cdot L^{-1}$. Chlorophyll measurements at the end of the post-production phase returned to a range (14 to 25 $\mu mol \cdot m^{-2}$) similar to the plants receiving 0 $mg \cdot L^{-1}$ paclobutrazol during the production phase (15 to 31 $\mu mol \cdot m^{-2}$) (Fig. 4.3B), although leaves in the 20 $mg \cdot L^{-1}$ paclobutrazol treatment remained greener than the 0 $mg \cdot L^{-1}$ paclobutrazol treatment at the termination of the post-production phase.

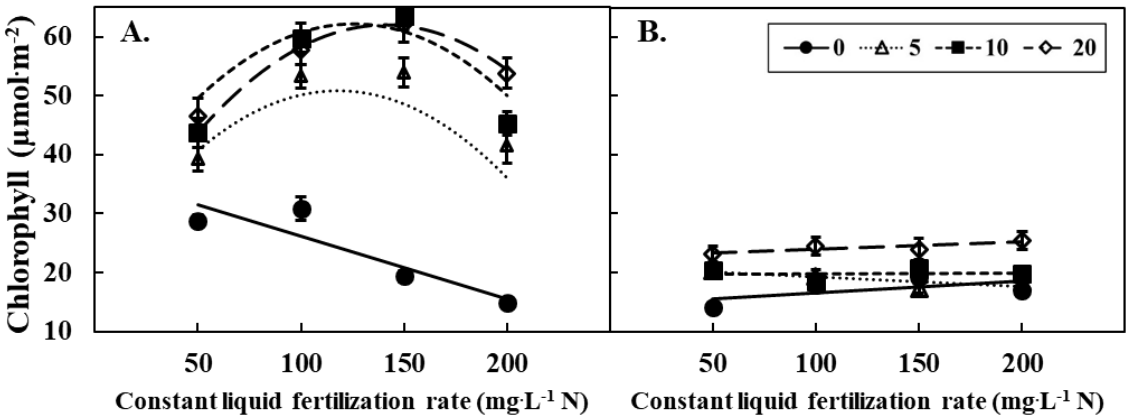

Fig. 4.3. Chlorophyll recorded at the end of the production phase (A) and post-production phase (B). Plants were treated with 50, 100, 150, or 200 mg·L^{-1} N constant liquid fertilization rates and 0, 5, 10, or 20 mg·L^{-1} paclobutrazol rates. Lines indicate significant linear or quadratic effects; $P < 0.05$ (n=24). Error bars represent ±1 SE.

Applying paclobutrazol had a slight delaying effect on the flowering of petunias, e.g., flowering was delayed by <2 days as paclobutrazol increased from 0 to 20 $mg \cdot L^{-1}$.

Plant fullness, defined as shoot fresh weight divided by plant height, measured at the end of the production phase increased with increasing CLF and paclobutrazol (Fig. 4.4A). The maximum fullness observed at 200 $mg \cdot L^{-1}$ N CLF with 20 $mg \cdot L^{-1}$ paclobutrazol was nearly twice that of the 100 $mg \cdot L^{-1}$ N CLF and 0 $mg \cdot L^{-1}$ paclobutrazol treatment. At the end of the post-production phase, effect of paclobutrazol was not significant, and CLF had little effect (Fig. 4.4B). For example, the fullness measurement of the 200 $mg \cdot L^{-1}$ N CLF and 20 $mg \cdot L^{-1}$ paclobutrazol treatment increased only by 16% compared with 100 $mg \cdot L^{-1}$ N CLF and 0 $mg \cdot L^{-1}$ paclobutrazol.

As expected, fuller plants with greener leaves were produced with increasing CLF and paclobutrazol. The effect of paclobutrazol on chlorophyll continued to be significant at the end of the post-production consumer phase, whereas the effect on plant fullness was not, suggesting that petunias successfully grew out of the paclobutrazol treatments while retaining foliar greenness.

Root fresh weight at the end of the production phase generally decreased with increasing paclobutrazol and increased with increasing CLF, but decreased at 200 $mg \cdot L^{-1}$ N CLF (data not shown). At the 100 $mg \cdot L^{-1}$ N CLF treatment, root fresh weight decreased 9% as paclobutrazol increased from 0 to 20 $mg \cdot L^{-1}$.

Media electrical conductivity increased with increasing CLF, but paclobutrazol was not significant at the end of the production phase (data not shown). Across all paclobutrazol treatments, media electrical conductivity increased from 0.8 to 3.1 $dS \cdot m^{-1}$ as

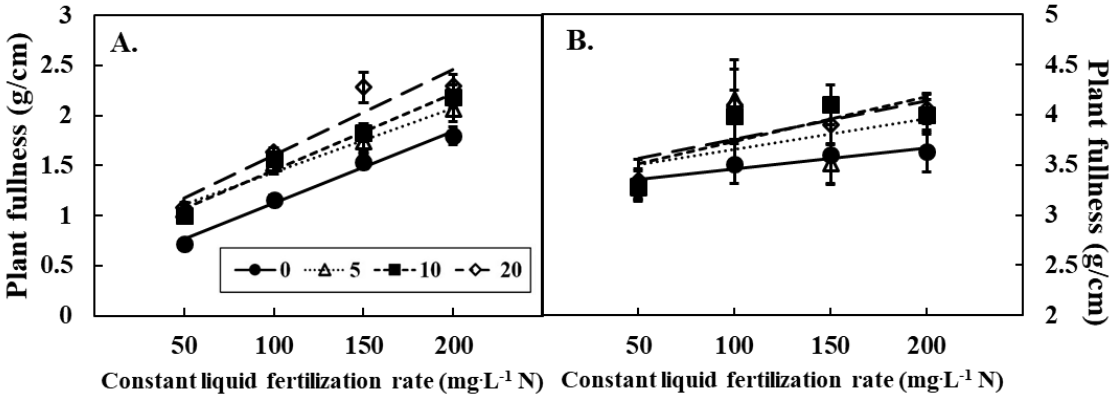

Fig. 4.4. Plant fullness (shoot fresh weight/plant height) recorded at the end of the production phase (A) and post-production phase (B). Plants were treated with 50, 100, 150, or 200 mg·L^{-1} N constant liquid fertilization rates and 0, 5, 10, or 20 mg·L^{-1} paclobutrazol rates. Lines indicate significant linear effects; $P < 0.05$ (n=24). Error bars represent ±1 SE.

CLF increased from 0 to 200 $mg \cdot L^{-1}$ N. At the end of the post-production phase, CLF was not significant, but media electrical conductivity increased with increasing paclobutrazol. Across all CLF treatments, media electrical conductivity increased from 1.9 to 3.5 $dS \cdot m^{-1}$ as paclobutrazol increased from 0 to 20 $mg \cdot L^{-1}$. The increase in media electrical conductivity with increasing paclobutrazol at the end of the post-production phase also poses a possibility that paclobutrazol enhances the longevity of petunia plants by reducing the rate of nutrient uptake. For example, paclobutrazol-treated plants are smaller, thus they require less water and fertilizer, resulting in more nutrients left in the growing medium that can enhance their longevity in the post-production consumer environment.

On the other hand, media pH decreased as CLF increased, and the effect of paclobutrazol was not significant at the end of the production. Across all paclobutrazol treatments, media pH decreased from 7.2 to 6.8. None of the treatments were significant at the end of the post-production phase for media pH. The total amount of nitrogen applied during the production phase averaged 20, 49, 81, or 118 mg/plant for each of the CLF treatments 50, 100, 150, or 200 $mg \cdot L^{-1}$ N, across all paclobutrazol treatments. The total amount of nitrogen applied during the production phase averaged 92, 61, 58, or 56 mg/plant for 0, 5, 10, or 20 $mg \cdot L^{-1}$ paclobutrazol treatments, across all CLF treatments.

Conclusions

In commercial petunia production, it is highly desirable to produce compact plants during production that then grow vigorously in the post-production environment. Therefore, the objective of this study was to achieve improved post-production performance with as

little CLF and paclobutrazol as possible. For final production quality, paclobutrazol application was more effective at reducing plant height than limiting CLF, since 5 $mg \cdot L^{-1}$ paclobutrazol reduced height by 53%, whereas 50 $mg \cdot L^{-1}$ N CLF reduced height by 35%, compared to the 100 $mg \cdot L^{-1}$ N CLF and 0 $mg \cdot L^{-1}$ paclobutrazol treatment. Moreover, plant fullness was reduced by 38% at 50 $mg \cdot L^{-1}$ CLF treatment, whereas it was increased by 31% at 5 $mg \cdot L^{-1}$ paclobutrazol, meaning that N-limiting strategy resulted in a reduced height but also a less full plant. After one month in consumer environment, paclobutrazol effects on growth and flowering lasted longer than CLF effects. Although plants that were treated with paclobutrazol did not fully catch up to the growth achieved by non-treated plants, they did show reduced impact on plant growth, suggesting that the paclobutrazol effect is slowly wearing off. An additional benefit of paclobutrazol was also observed, characterized by the prolonged foliar greenness and higher nutrient reserve remaining in the pot at the post-production phase. In conclusion, paclobutrazol is more effective at reducing plant height of petunias compared to N-limitation, and when applied at a low enough rate, it can provide the benefits with post-production consumer performance while minimizing the long-term reduction in growth.

APPENDICES

Appendix A

Pictures

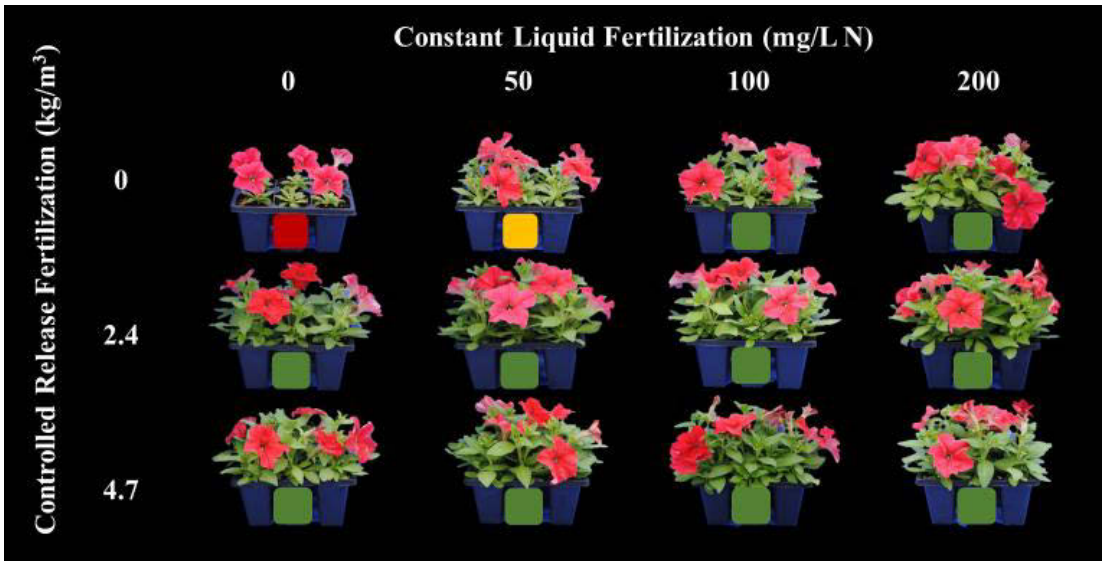

Fig. A.1. Petunias at the end of the production phase (Chapter 3, Rep 1)

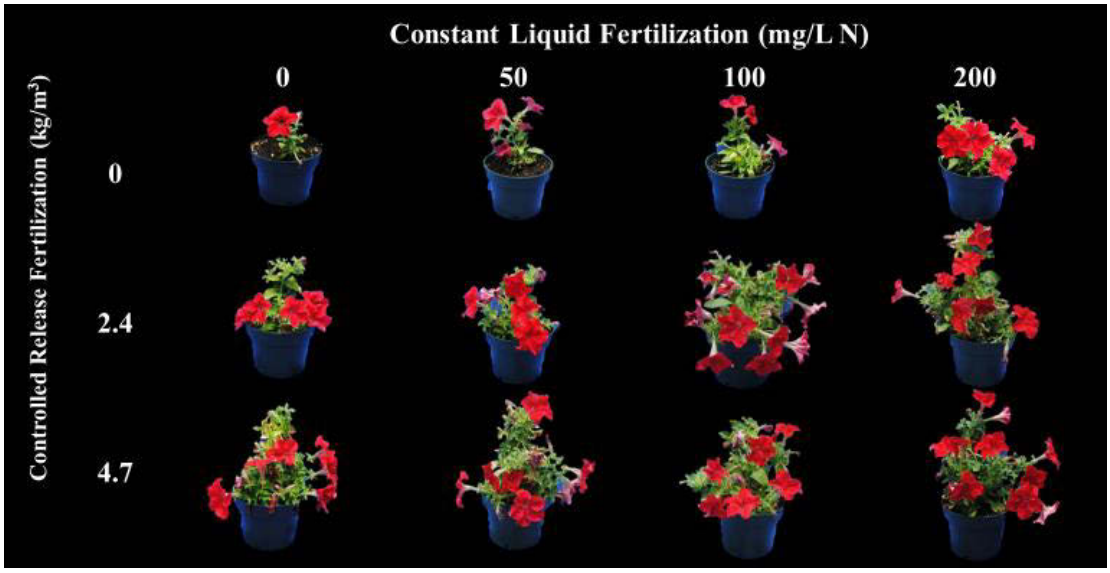

Fig. A.2. Petunias treated with 0 $mg \cdot L^{-1}$ N pulse fertilization, at the end of the post-production phase (Chapter3, Rep 1)

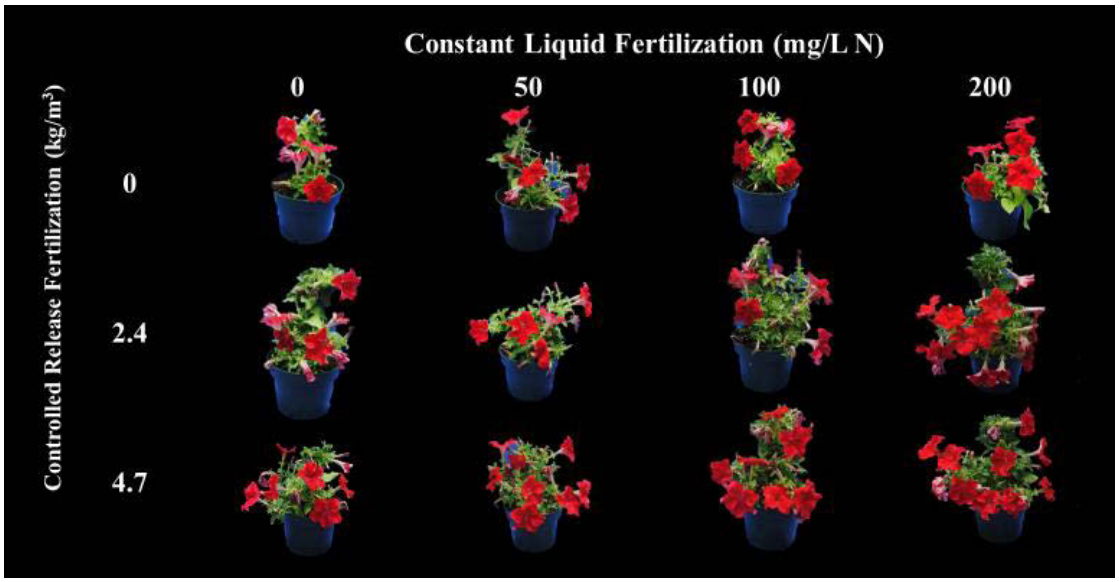

Fig. A.3. Petunias treated with 600 $mg \cdot L^{-1}$ N pulse fertilization, at the end of the post-production phase (Chapter3, Rep 1)

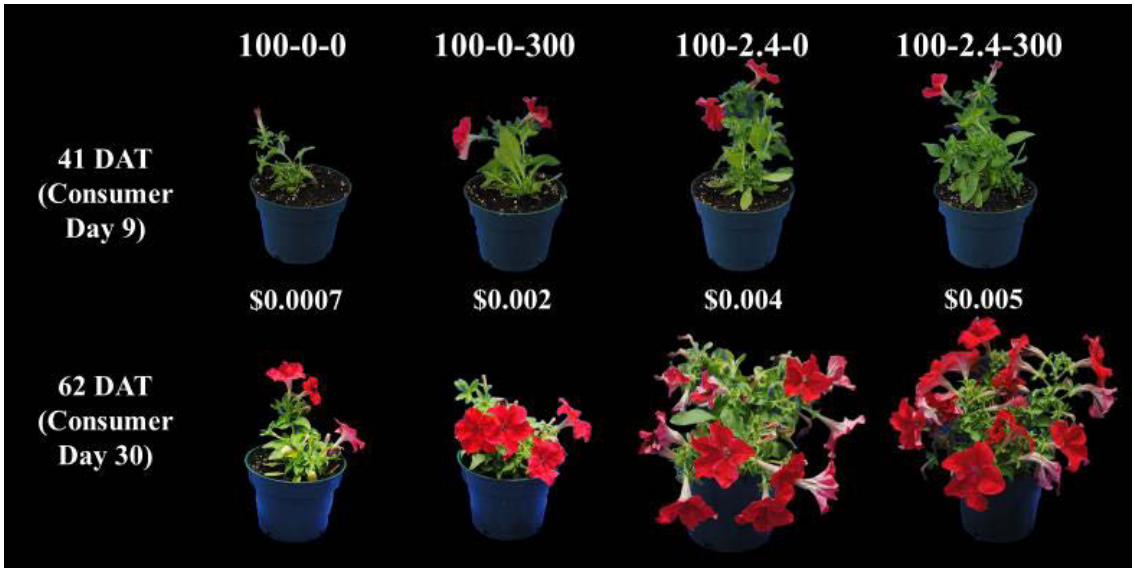

Fig. A.4. Petunias at 41 or 62 days after transplant. Treatments indicate in the order of constant liquid fertilization ($mg \cdot L^{-1}$ N) - controlled release fertilization ($kg \cdot m^{-3}$) - pulse fertilization ($mg \cdot L^{-1}$ N). The cost indicates per 6-pack container. (Chapter 3, Rep 1)

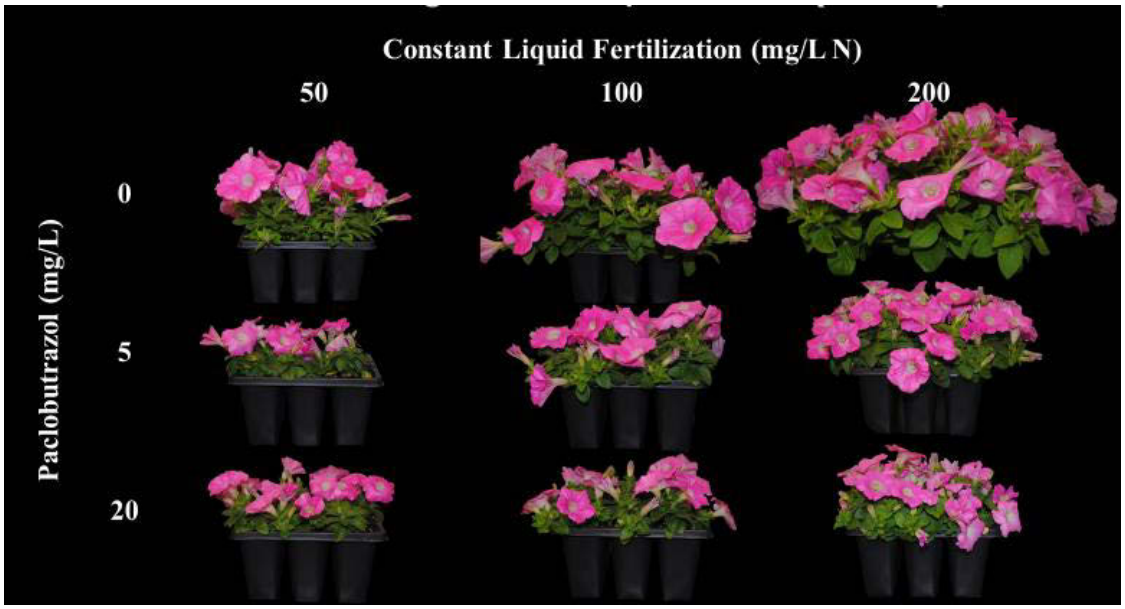

Fig. A.5. Petunias at the end of the production phase (Chapter 4, Rep 1)

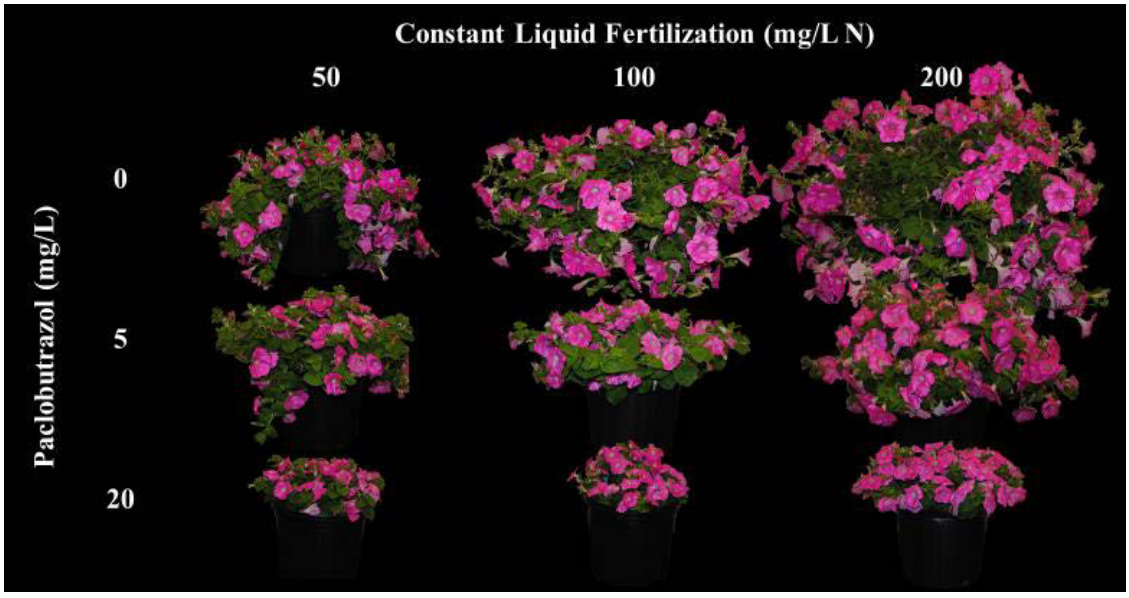

Fig. A.6. Petunias at the end of the post-production phase (Chapter 4, Rep 1)

Appendix B

Nutrient Analysis Results from Day 1

Table B.1. Tissue nutrient analysis results from Day 1 (Chapter 3, Rep 1&2)

----------% dry weight----------						$mg \cdot kg^{-1}$
N	**P**	**K**	**Ca**	**Mg**	**S**	**Fe**
2.5	0.4	4.2	1.1	0.6	0.4	910

Table B.2. Media nutrient analysis results from Day 1 (Chapter 3, Rep 2)

----------% dry weight----------						$mg \cdot kg^{-1}$
N	**P**	**K**	**Ca**	**Mg**	**S**	**Fe**
0.8	0.02	0.02	2.9	1.7	0.1	991

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